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STUDY OF MAN PULLING A CART ON THE MOON

by A. Camacho, W. Robertson, and A. Walther

Prepared by
AIRESEARCH MANUFACTURING COMPANY
Los Angeles, Calif.
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16. Abstract

This paper presents the results of a study made to evaluate the metabolic cost of self-locomotion in simulated lunar gravity using an EX-IA suit. The use of a cart as a load-carrying device was also evaluated. The tests were performed in a simulator using a blow-by piston suspension system. The effects of surface grades, surface characteristics, backpack weights, and cart weights on metabolic cost for various locomotive rates were determined. The range of surface characteristics investigated had only a small effect on the metabolic costs of locomotion. Pulling a cart weighing 165 pounds, earth weight, on a level surface did not increase the energy cost of locomotion over that obtained without the cart.

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AiResearch Manufacturing Company

SECTION I.- INTRODUCTION

This report presents the results, methods, procedures and apparatus of an exploratory study to evaluate a blow-by piston lunar gravity suspension system and to evaluate the metabolic cost of human locomotion in an EX-1A space suit at simulated 1/6 g. This program was conducted by the AiResearch Manufacturing Company, Los Angeles, a division of The Garrett Corporation for NASA/Langley Research Center under Phase III of Contract NAS 1-7053. The objective of this test program was to investigate the effect of surface grades, lunar surface conditions, backpack weights, pull cart weights, velocity, and locomotive gait on metabolic cost using a blow-by piston lunar gravity suspension system.

The experimental design of the tests performed is shown in table 1-1. These exploratory tests were selected to provide similar test conditions for comparison to previous lunar gravity metabolic studies and to show the effects of slope grade, lunar soil, and pull carts on metabolic cost.

TABLE 1-1.-- EXPERIMENTAL CONDITIONS

Simulator and suit mode	Surface condition	Slope, deg	Gait	Velocity, km/hr	Backpack weight, lb	Pull cart weight, lb	Total tests
Blow-by air piston suspension system Pressurized space suit at 3.7 psig	Coarse lunar soil simulant (dry, coarse soil)	0	Walk	2 and 4	75 and 240	--	24
			Run	6 and 8			
			Lope	6 and 8			
		+15	Walk	2 and 4	75 and 240	--	16
		-15					
	Apollo 11 soil simulant (cohesive soil)	0	Walk	2 and 4	75	--	20
			Run	6 and 8			
			Lope	6 and 8			
		+15	Walk	2 and 4	75	--	20
		-15					
		0	Walk	2,3,4, and 5	75	165 and 325	16
		+15	Walk	2 and 4	75	165 and 325	16
		-15					

SECTION 2.- FACILITIES AND APPARATUS

The tests were conducted at the AiResearch lunar simulation test facility shown in fig. 2-1. The variable surface treadmill system, physiological and metabolic apparatus, digital data system, environmental control system, and computerized data reduction system are described in detail in NASA Contractor Report NASA CR-1402, Man's Capability for Self-Locomotion on the Moon (ref. 1).

To improve the lunar gravity simulation, the Turbine Operated Suspension System (TOSS) was modified to provide better dynamic response than that provided in earlier tests. The drive turbine on TOSS was replaced by a blow-by piston to provide the vertical degress of freedom. The "C" brace-gimbal method of providing six degrees of freedom was replaced by a whiffle tree suspension. The variable surface treadmill system was modified to meet the testing requirements. A lunar pull/push cart was designed for evaluation as a load carrying device.

BLOW-BY PISTON SUSPENSION SYSTEM

Lunar gravity similation was provided by a blow-by suspension system. The system was designed and developed by AiResearch with the intent of providing a constant vertical force and low inertial and frictional forces during system operation. Fig. 2-2 shows the blow-by piston installation. An overall view of the variable lunar surface treadmill and the blow-by piston system is shown in fig. 2-3.

The basic system which provides the six degrees of freedom desired for reduced gravity simulation consists of a whiffle tree design support system, a swivel, a yoke with an air-pad bearing, cable and pulleys, a lightweight pivoted beam with air pads, and a blow-by piston take-up. The system is shown in fig. 2-4. The pulley arrangement allows the whiffle tree support to remain at a constant height during fore and aft movements of the yoke and air pad assembly. The sources of the degrees of freedom with reference to the subjects' center of gravity are listed in table 2-1.

Blow-by Piston

Vertical lift by the blow-by piston suspension system was achieved by aerodynamic drag forces acting on a loose-fitting piston within a long guide tube. A turbocompressor supplied a high flow of air to the inlet of the tube. The piston, which was free to move back and forth was kept centered and aligned by Teflon guide pads. The piston was connected by a cable to the whiffle tree support and yoke assembly. When the piston moved forward or aft, the pressure differential across the piston increased or decreased. The velocity at which the piston moved determined the amount of pressure change. A pressure regulator limited the pressure changes by increasing or decreasing the bypass airflow and thus tended to maintain a constant vertical force. The pressure regulator is dome operated for remote control of the piston pressure and therefore the cable tension force. A schematic of the blow-by piston design is shown in fig. 2-5.

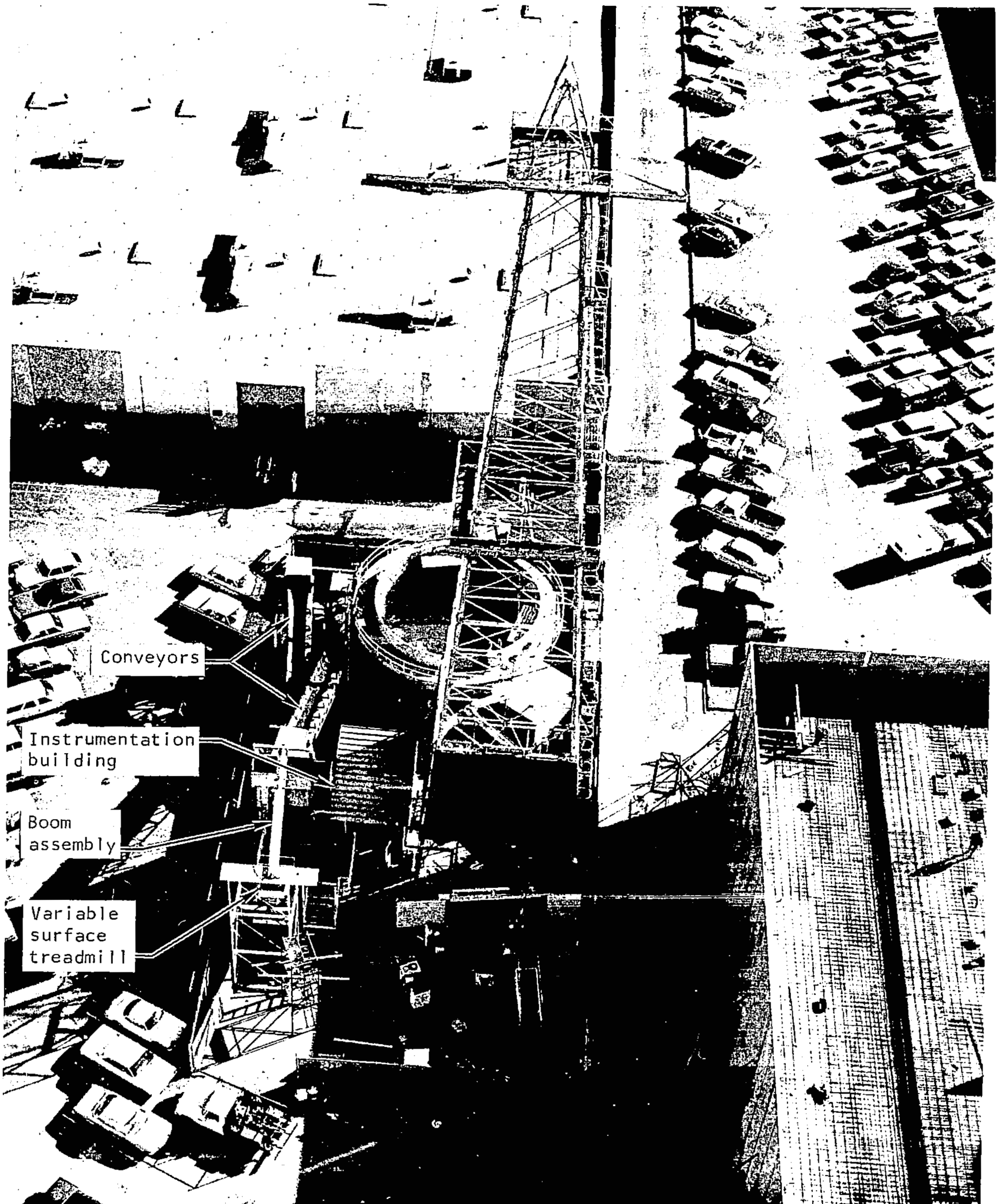

Fig. 2-1. AiResearch lunar simulation test facility

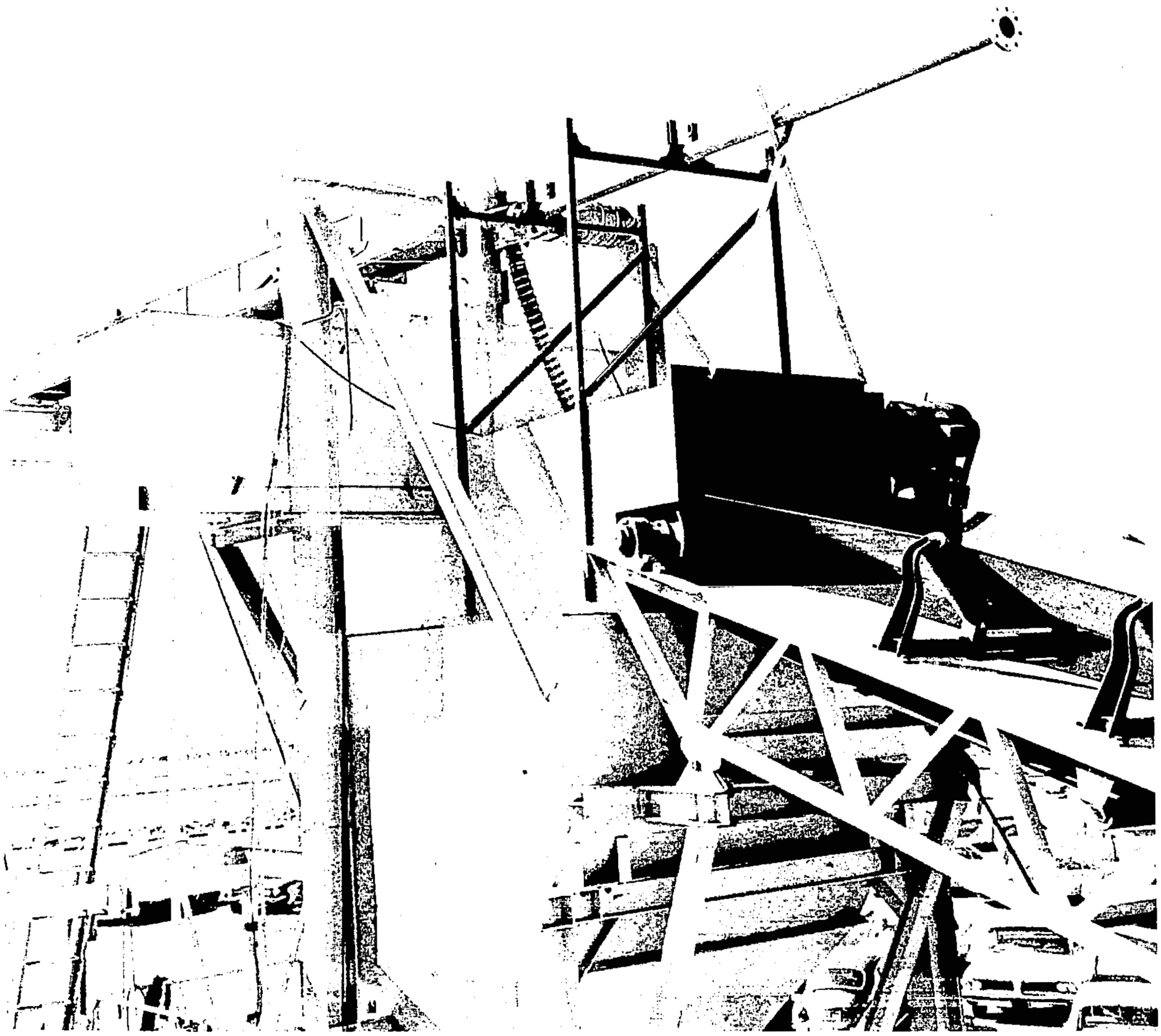

Fig. 2-2. Blow-by piston installation

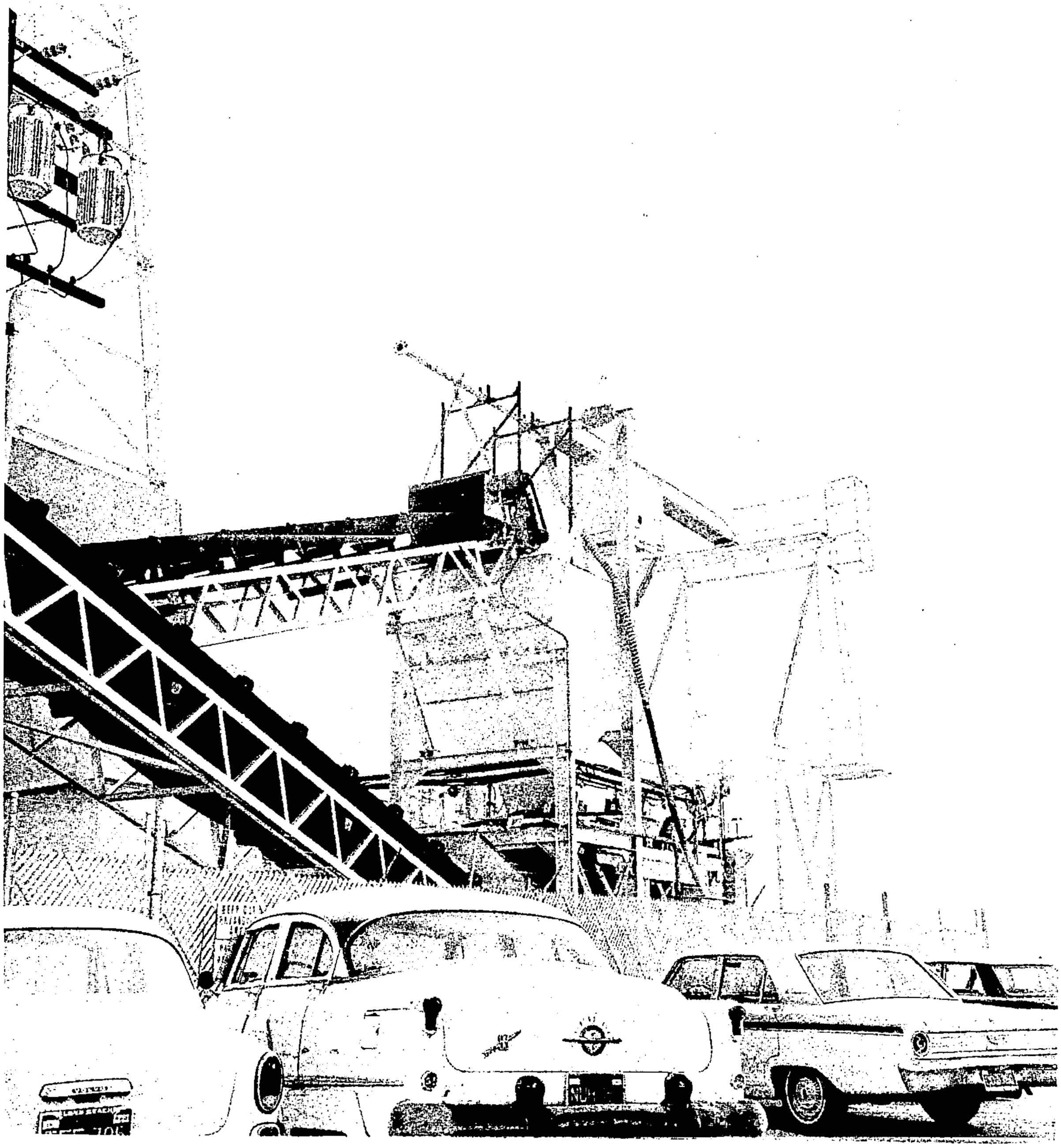

Fig. 2-3. Variable lunar surface treadmill and the blow-by piston system

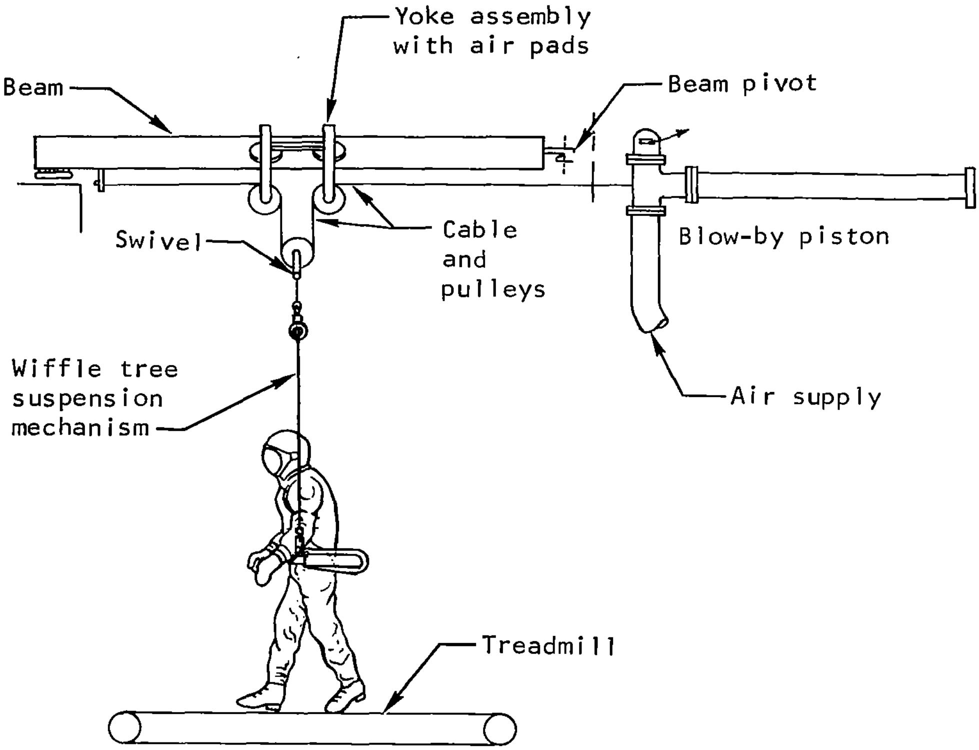

Fig. 2-4. Blow-by piston suspension system

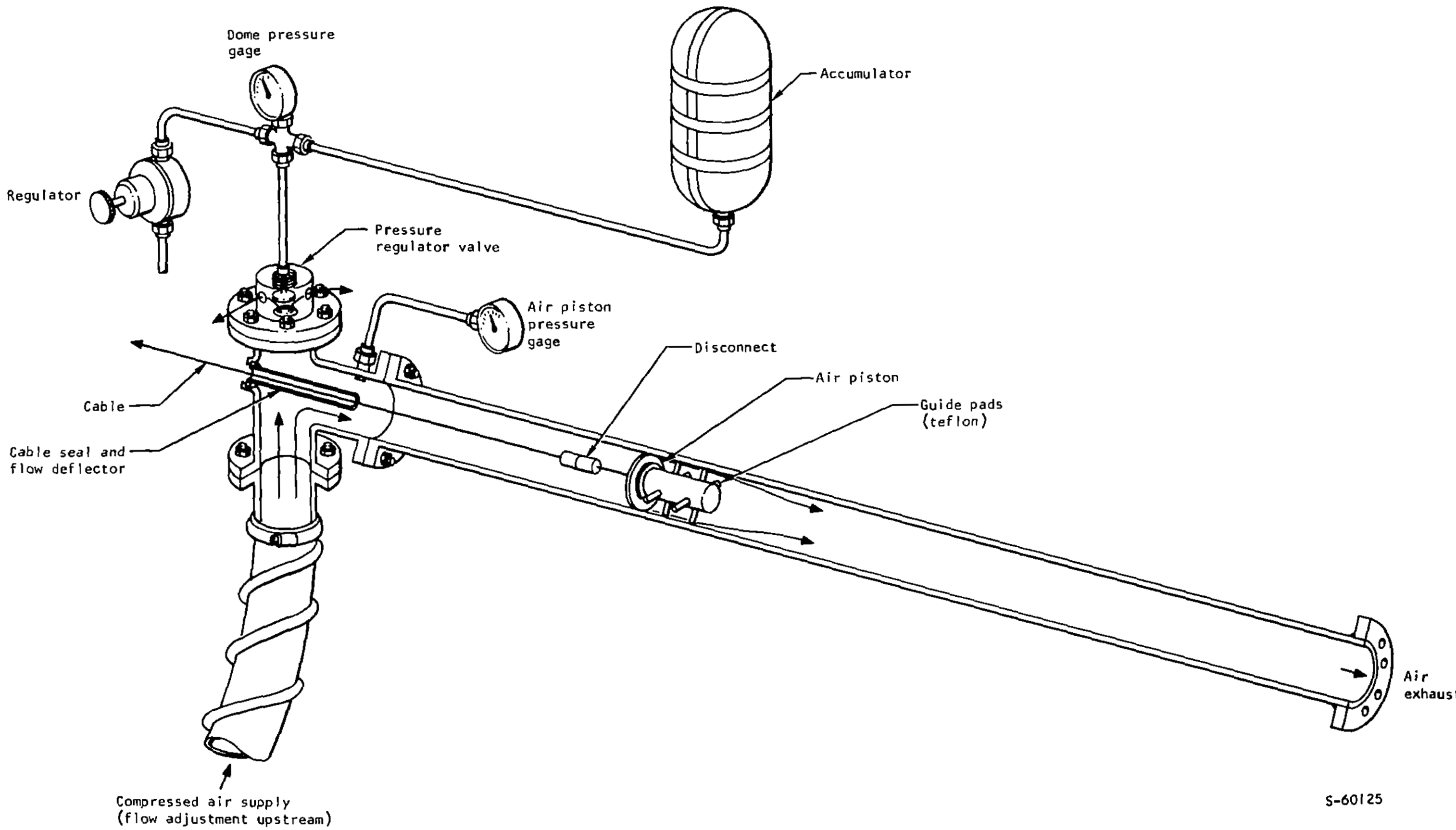

Fig. 2-5. Blow-by suspension assembly

TABLE 2-1.-- BLOW-BY SUSPENSION SYSTEM DEGREES OF FREEDOM

Component	Type of freedom	Degrees of freedom
Whiffle tree support	Pitch and roll	2
Swivel	Yaw	1
Blow-by piston take-up	Vertical	1
Yoke (with air pads)	Fore and aft	1
Beam (pivot and air pads)	Lateral	1
Total degrees of freedom		6

Blow-by Piston Suspension Tests

Pulley/blow-by piston frictional force test.- As part of the continuing modification to reduce frictional drag and inertial effects of the pulleys and cables, the suspension cable diameter was reduced from 3/16 in. to 1/8 in.

The weight of an EX-1A suited subject with a 75-lb backpack was approximately 290 lb. The 1/6-g cable tension force for 290 lb is 242 lb. To determine the frictional force inherent in the pulleys and blow-by piston, a 242 lb weight was balanced as shown in fig. 2-6. A force of 3 lb was necessary to change the direction of movement of the suspended mass from slowly rising to slowly falling. The frictional force of the blow-by piston suspension system was ±1.5 lb.

Dynamic Tests.- To evaluate the dynamic characteristics of the blow-by suspension system, a vertical velocity was imparted to a suspended mass (290 lb) equivalent to EX-1A suited subject with a 75-lb backpack at 1/6 g. The suspended mass was then allowed to free-fall in the vertical direction. The equations of motion of a free-falling object with an initial upward velocity V_o and constant acceleration a are

$$\text{Maximum height, } h_{max} = \frac{V_o^2}{a}$$

$$\text{Total free-flight time, } t = \frac{2V_o}{a}$$

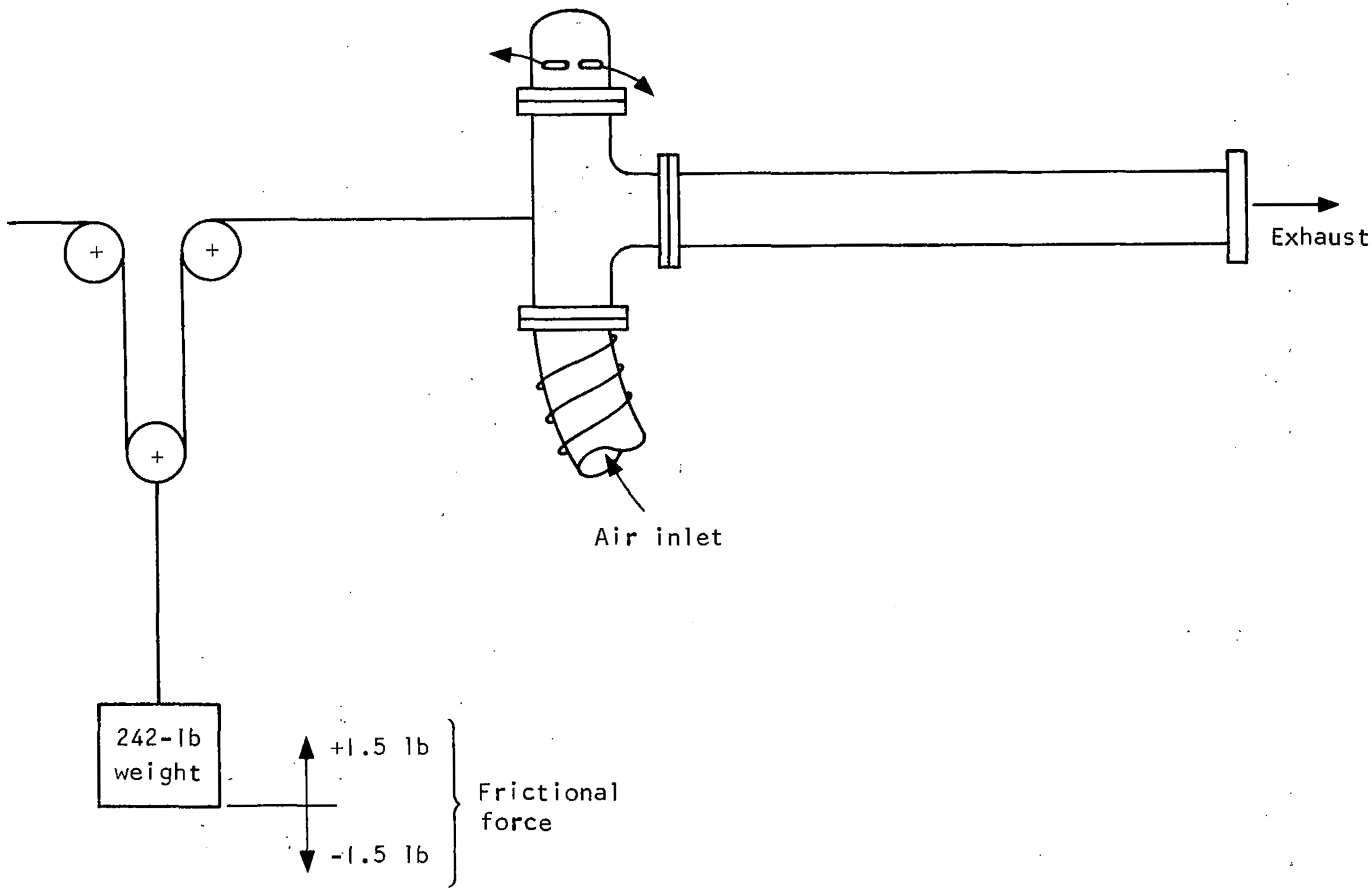

Fig. 2-6. Test setup for determination of the blow-by suspension system friction

The dynamic test set-up is shown in fig. 2-7. A pneumatic piston provided the the driving force. Varying the airflow rate through a manual shutoff valve changed the velocity imparted to the suspended weight. The velocity gradient during the start up was nonlinear but approached a constant value at the end of the 18-in. piston stroke.

Pressure transducers measured the blow-by piston pressure and the pressure regulator valve dome pressure. A reel-type position transducer mounted at the center of the overhead air-pad trolly measured the position of the weight. A piston/weight contact switch measured the free-flight time. A load cell attached between the weight and load pickup cable measured the changes in pickup cable tension. The blow-by piston pressure, pressure regulator dome pressure, drive piston pressure, drive piston position, contact switch position, and load cell signal were all recorded on an oscillograph recorder.

A total of 29 test runs were made at heights of 4, 10, and 20 in. Three repetitions at each height were recorded. The results of test No. 19, which was selected for analysis, are shown in fig. 2-8.

The curve defined by the movement of the weight closely resembles a parabola as shown in fig. 2-9. An initial velocity (V_e) was determined by establishing a tangent to the slope of the parabola at the point of separation of the mass from the actuator and calculating the cotangent function. This results in a calculation of the distance traveled versus the time expended for the weight:

$$V_e = \frac{\text{distance weight traveled}}{\text{time expended}}$$

If a preseparation time versus distance relationship had been used, the initial velocity would have been biased by other than the system dynamic impedances. The recorded curve was then compared with an ideal parabola, $y = ax^2 + bx + e$, constructed using the established initial velocity and a 1/6-g acceleration constant. The major comparative characteristics of the actual curve with the ideal for the 20-in. jump are as follows:

	Actual	Ideal	Difference
Total time duration, sec	1.6264	1.6616	0.0352
Maximum height of curve, in.	20.264	21.863	1.599
Time of maximum height, sec	0.7528	0.8308	0.0780

The implication of the above data is that a constant acceleration was not realized, and the test system was affected by system dynamic operational impedances affecting transient operation; however, information realized from a simulation of this type is valid.

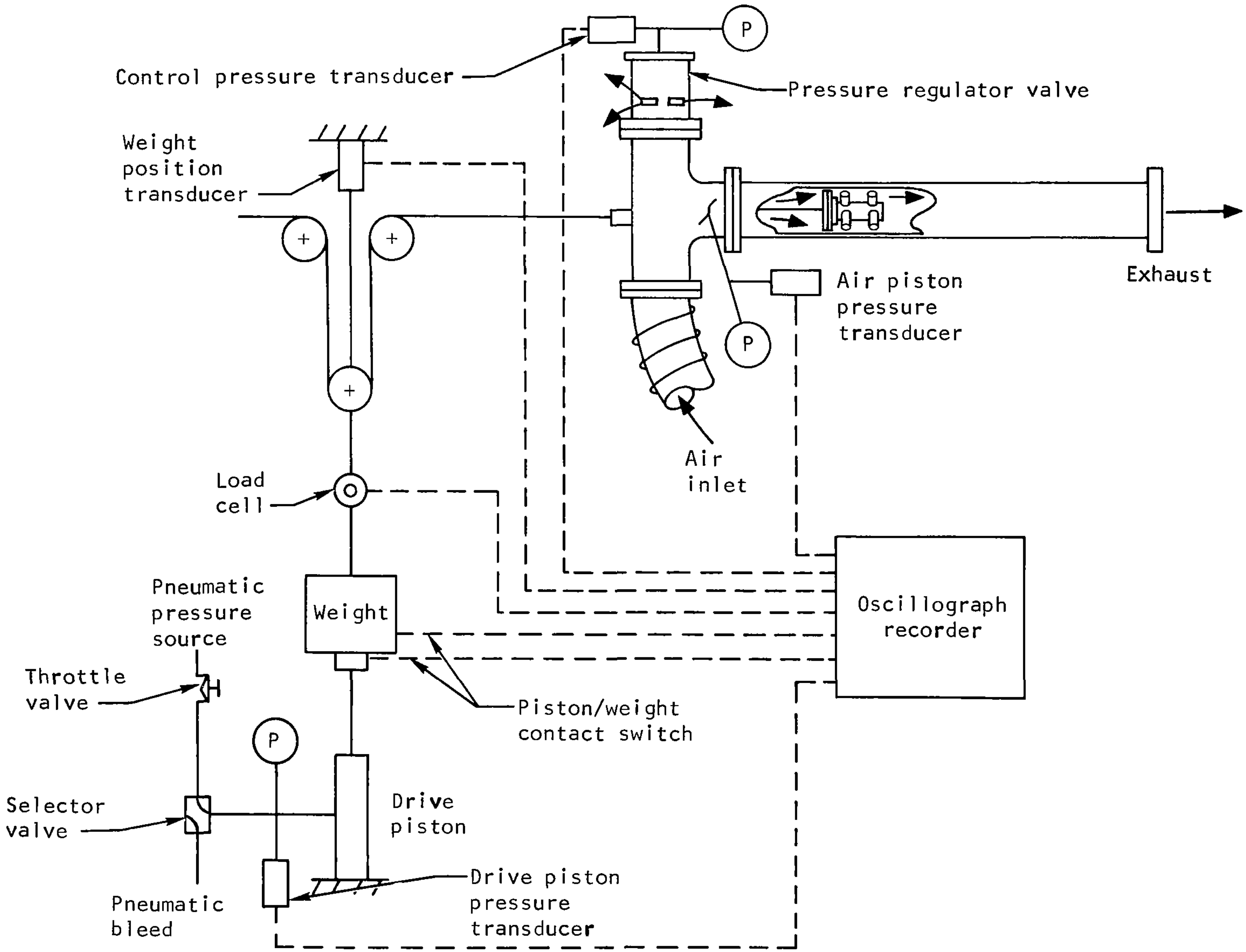

Fig. 2-7. Dynamic test setup of blow-by suspension system

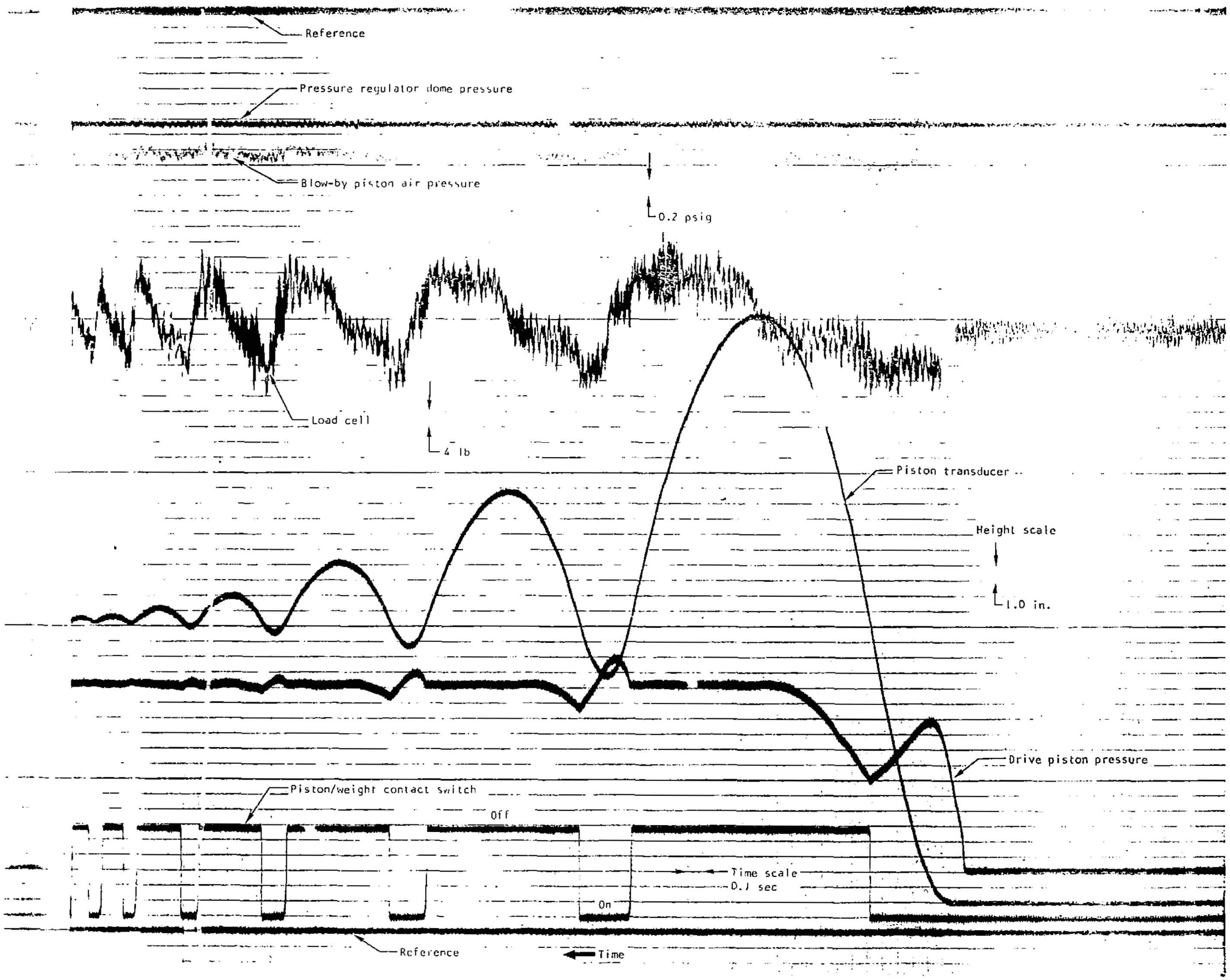

Fig. 2-8. Blow-by piston dynamic test No. 19

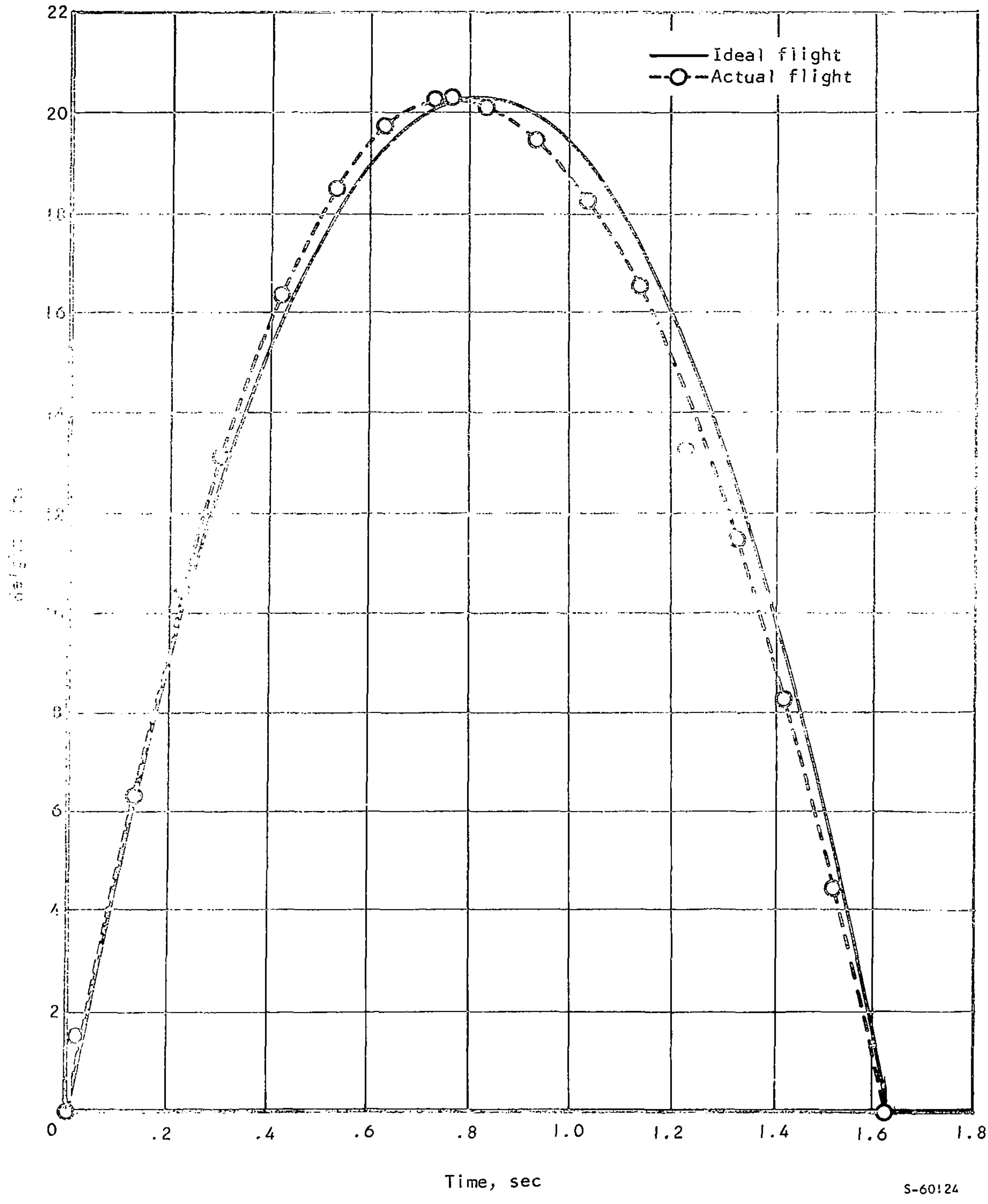

Fig. 2-9. Comparison of actual and ideal flight parabolas

The use of the initial velocity is the best method of comparison since only the liftoff velocities are equal in both the ideal and actual cases. Computing the initial velocity or acceleration by a curve fitting program introduces an inherent error because the polynomial curve fit equation derived will wander plus or minus along the actual curve. As the order of the polynomial i.e., 1, 2, 3, increases, the error will be compounded. The equations of motion for free-fall are of the second order; therefore, the curve fitting program should only go up to the second order. The derivative of this second-order equation to compute the initial velocity introduces more of an error than graphically measuring the velocity from the actual data.

To graphically determine the acceleration profile from the actual data would introduce a gross error, especially at the top of the curve where the curve is almost flat. Using a second degree equation for a curve fitting solution minimizes the error introduced when taking a derivative of N order polynomial equation curve fit. The average acceleration determined for the actual simulation ranges between 59.1 to 61.3 in./sec^2 over the flight.

A plot of 1/2 (mV) vs V is shown in fig. 2-10 for comparison. The product of the abscissa and ordinate realizes kinetic energy. The ideal and actual 1/2 (mV) vs V plots represent lines with identical slopes. The variance in the descending end point is caused by test setup dynamic impedances, and this variance can be used to measure the energy used by the test setup. The kinetic energy difference is that represented by the shaded area. The total kinetic energy expended in the mechanics of the test set is approximately [illegible], corresponding to a -12.6 percent error in total energy over the 20-in. jump.

This analysis is only for the 20-in. jump, and no inference of a constant -12.6 percent energy loss for all vertical excursions is warranted without further analyses of other jump heights. The meaning of this energy loss to the subject cannot be evaluated with respect to the energetic cost of a locomotion gait utilizing a 20-in. excursion such as the loping gait.

Whiffle Tree Support

A whiffle tree support was required to replace the "C" brace gimbal support system used on the TOSS suspension. The design objective was a light weight, low inertia, dynamically balanced support system. General design of the whiffle tree supports was presented to NASA/Langley for their review and approval. Roll-axis and pitch-axis whiffle tree designs are shown in fig. 2-11 and fig. 2-12. The choice was to fabricate a roll axis whiffle tree.

The whiffle tree support acts on the principle of a parallelogram. Two bars connected together with equal length cables will follow each other to provide rotation but no lift at the center of each bar. Also, the whiffle tree is statically and dynamically balanced because of its shape. Dimensional data and degree-of-freedom ranges for the whiffle tree suspension rig are shown in fig. 2-13.

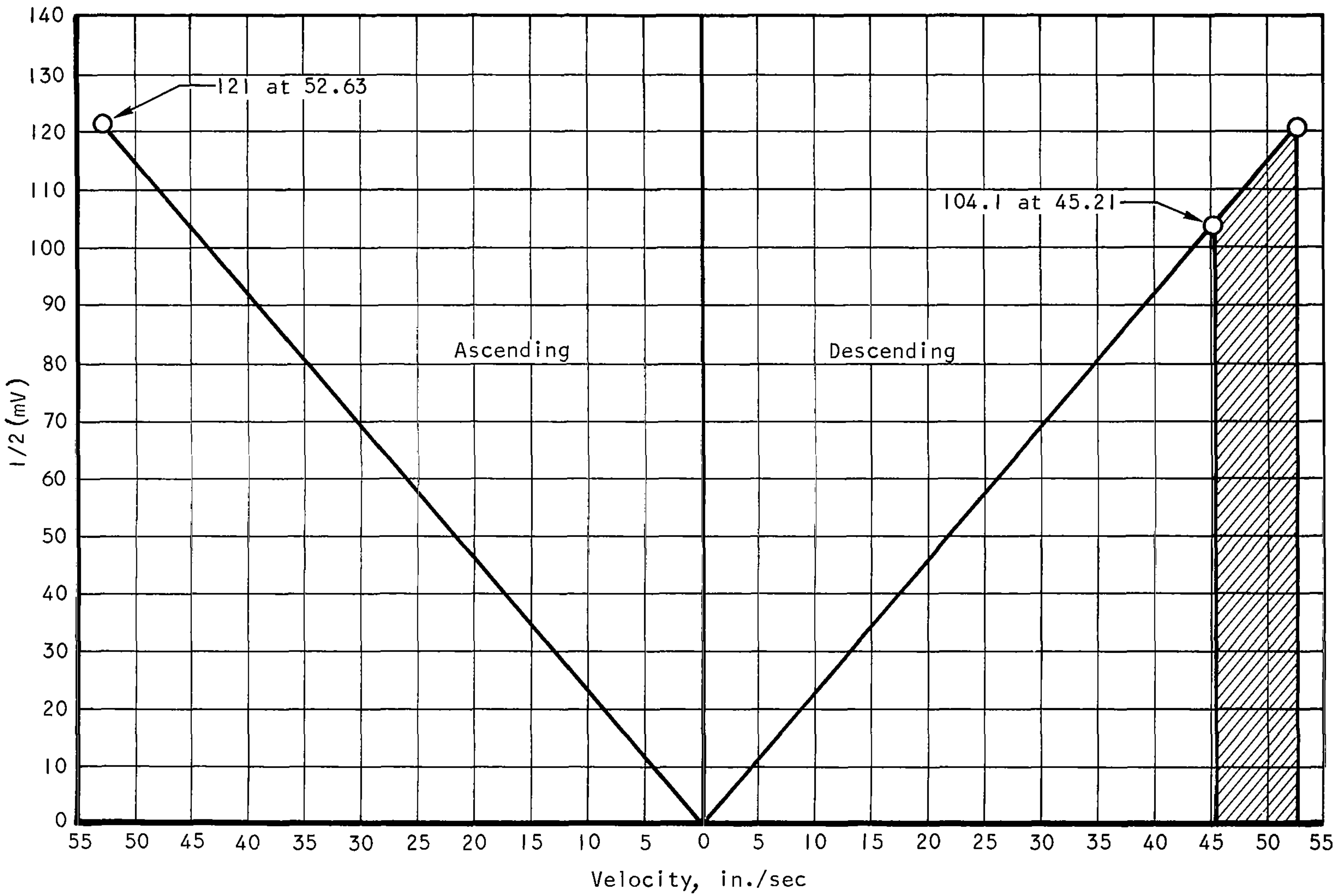

Fig. 2-10. Variation of I/2 (mV) versus velocity for a 20-in. displacement

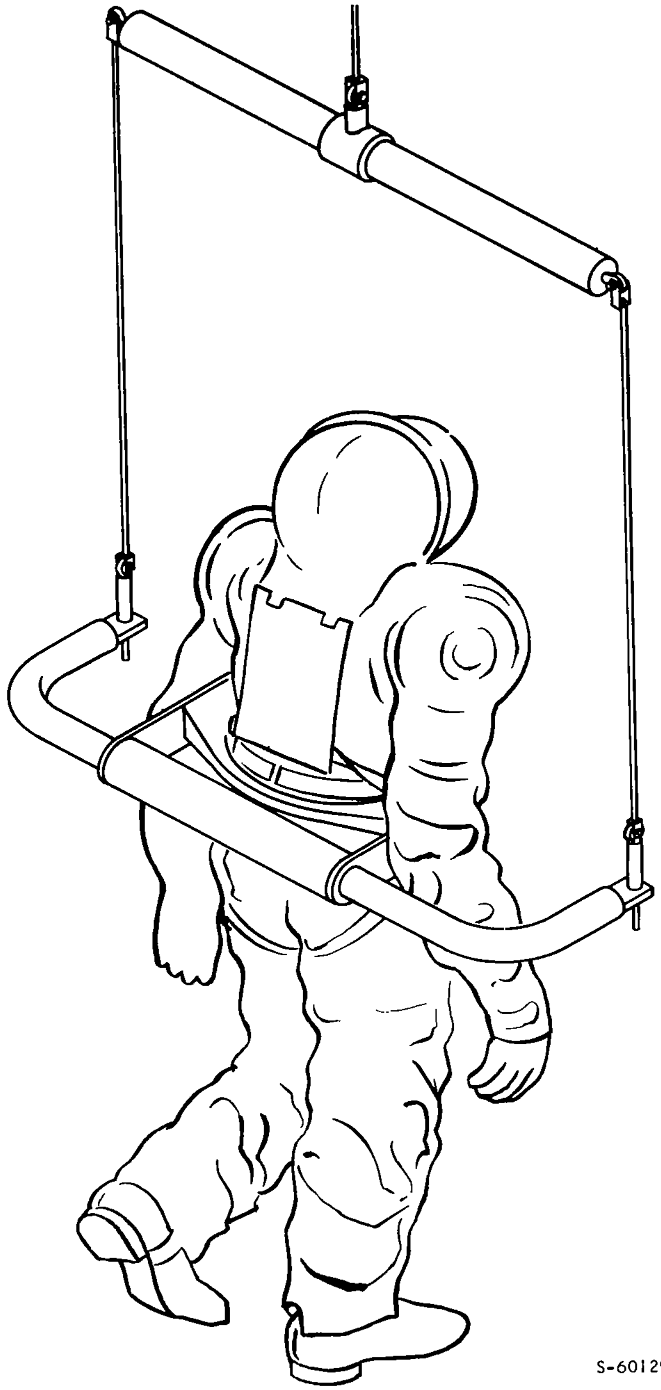

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Fig. 2-11. Roll axis whiffle tree design

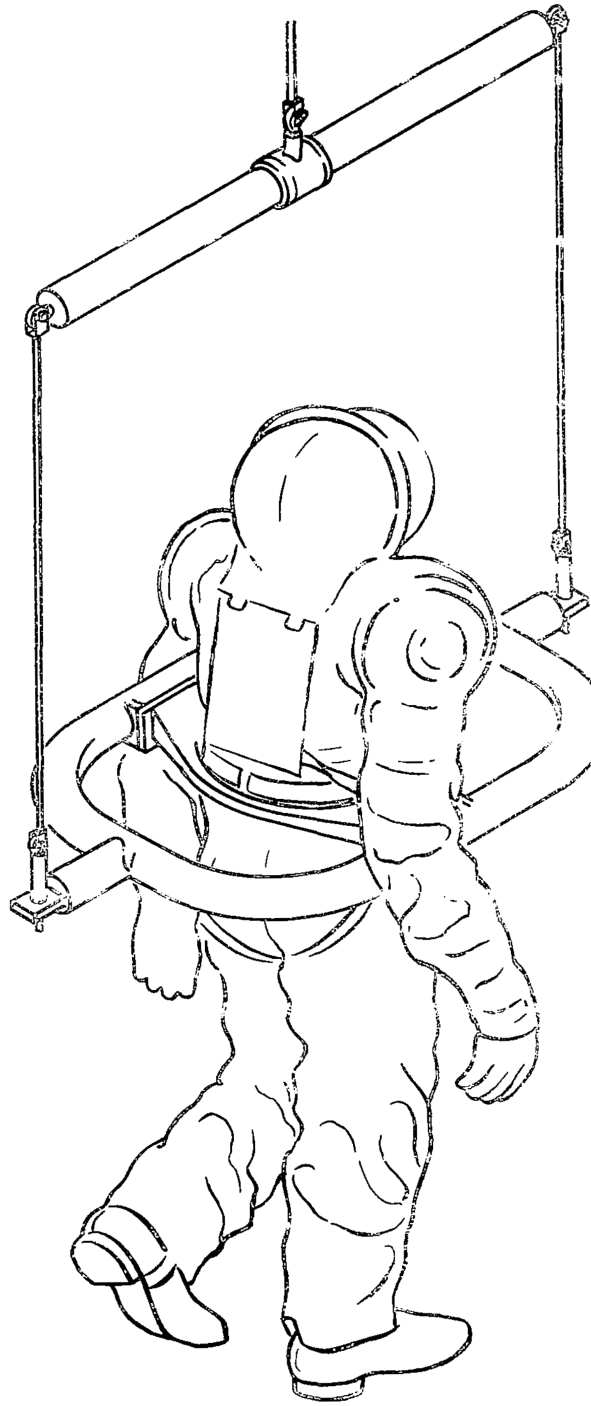

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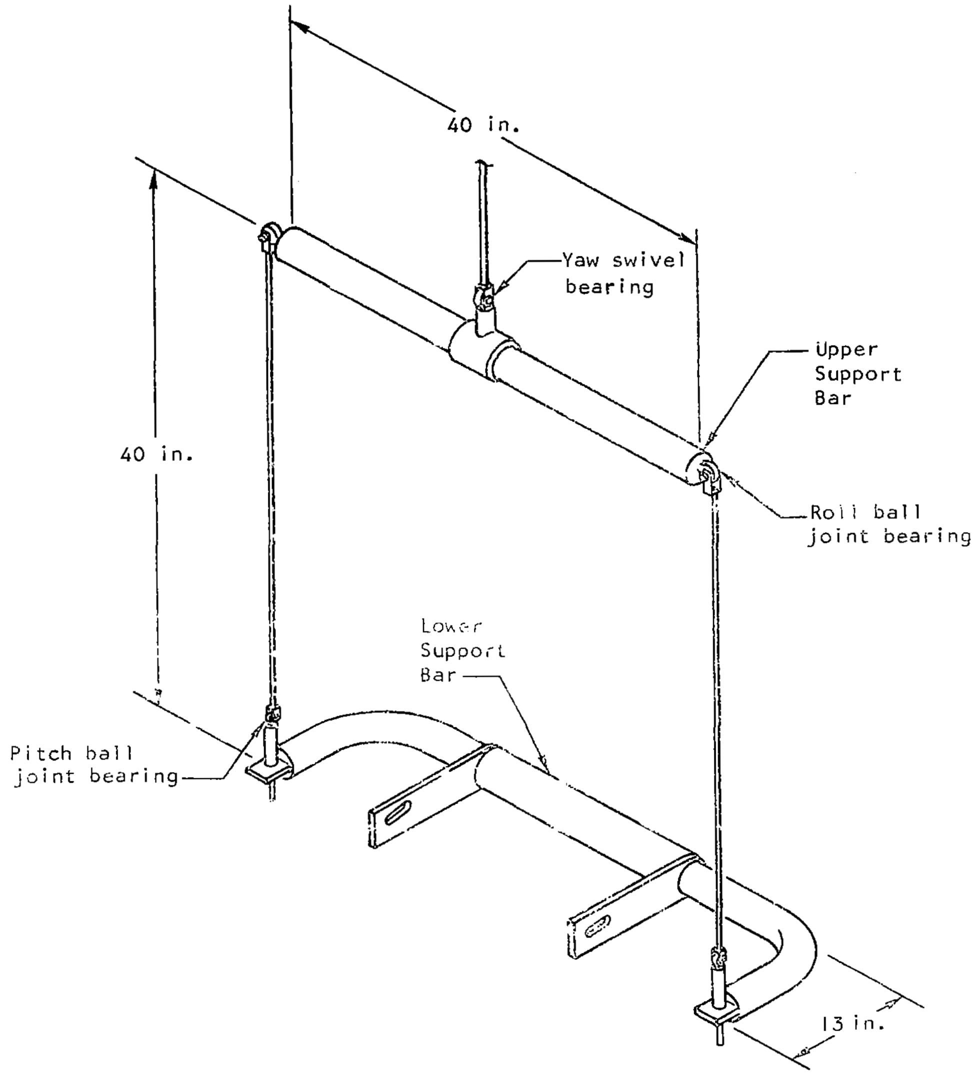
Fig. 2-12. Pitch axis whiffle tree design



Whiffle tree suspension three degrees of freedom

Component	Range, degrees	Degrees of freedom
Yaw swivel bearing	±90	1
Pitch ball joint bearing	±60	1
Roll ball joint bearing	±15	1
Total degrees of freedom	---	3

S-60130

Fig. 2-13. Final whiffle tree design characteristics

The roll axis whiffle tree support consists of two main parts: the upper support bar and the lower support bar. The ends of each bar are provided with swivel bearings. The center of the upper bar also has a swivel bearing. These five bearings provide a limited $\pm 15^{\circ}$ angular rotation. The ends of each bar are connected by two plastic covered steel cables 40 in. long. The bearing in the center of the upper bar is connected to the blow-by suspension pickup cable. The lower bar is shaped like a shallow "U." The swivel bearings on each end of the lower bar are adjustable to provide an easy up and down adjustment of the subject's center of gravity. The center of the lower bar has two pickup arms which bolt directly to a special pickup ring for supporting the EX-IA space suit. The two arms are slotted for fore and aft adjustment of the subject's center of gravity. Figs. 2-14 and 2-15 are photographs of the lower half of the whiffle tree.

The roll axis whiffle tree is constructed primarily of large diameter, thin-wall aluminum tubes for weight and strength considerations. The entire roll axis whiffle tree support including the EX-IA support ring weighs approximately 18 lb.

The EX-IA support ring consists of two welded and machined aluminum elliptical halves. Their cross section is "U" shaped to slip over the hip support ring of the EX-IA suit. Both halves are clamped together by quick acting clamps. The sides of the pickup ring are reinforced to provide a mounting surface. Fig. 2-16 shows the EX-IA pickup ring bolted to the lower half of the whiffle tree.

EX-IA Upper Torso Piston

It was found in early testing that the waist joint of the EX-IA was causing a problem in 1/6-g simulation. It was noted that by picking up the EX-IA suit through the lower torso section, the upper half of the suit was still in a 1-g field. The convolute design of the upper torso allows the torso to rotate about the roll or pitch axis. During the earlier checkout tests, the subject complained of an undue strain to their lower back. Examination of the method of suit suspension showed the upper half was not supported and its weight of approximately 20 lb was carried as a load on the subject's back. In previous pressure suits tested this problem did not occur because these suits had stiff, solid torso sections.

To eliminate this problem a small air piston was attached to the front of the EX-IA suit pickup ring to provide a balancing force to the upper half of the torso. The piston was adjusted to keep the torso erect without any load on the subject. The piston allowed approximately $\pm 3/4$-in. piston travel from the neutral position.

The piston did not affect the upper torso in the roll axis. The subject balanced himself about the roll axis by lateral extension of his arms. Figs. 2-17 and 2-18 show the piston attached to the suit. The upper torso piston support was adjusted to approximately 15 psig to counterbalance the weight of the suit's upper torso. The subject's backpack or lunar cart or both were then attached as necessary for the particular test requirement.

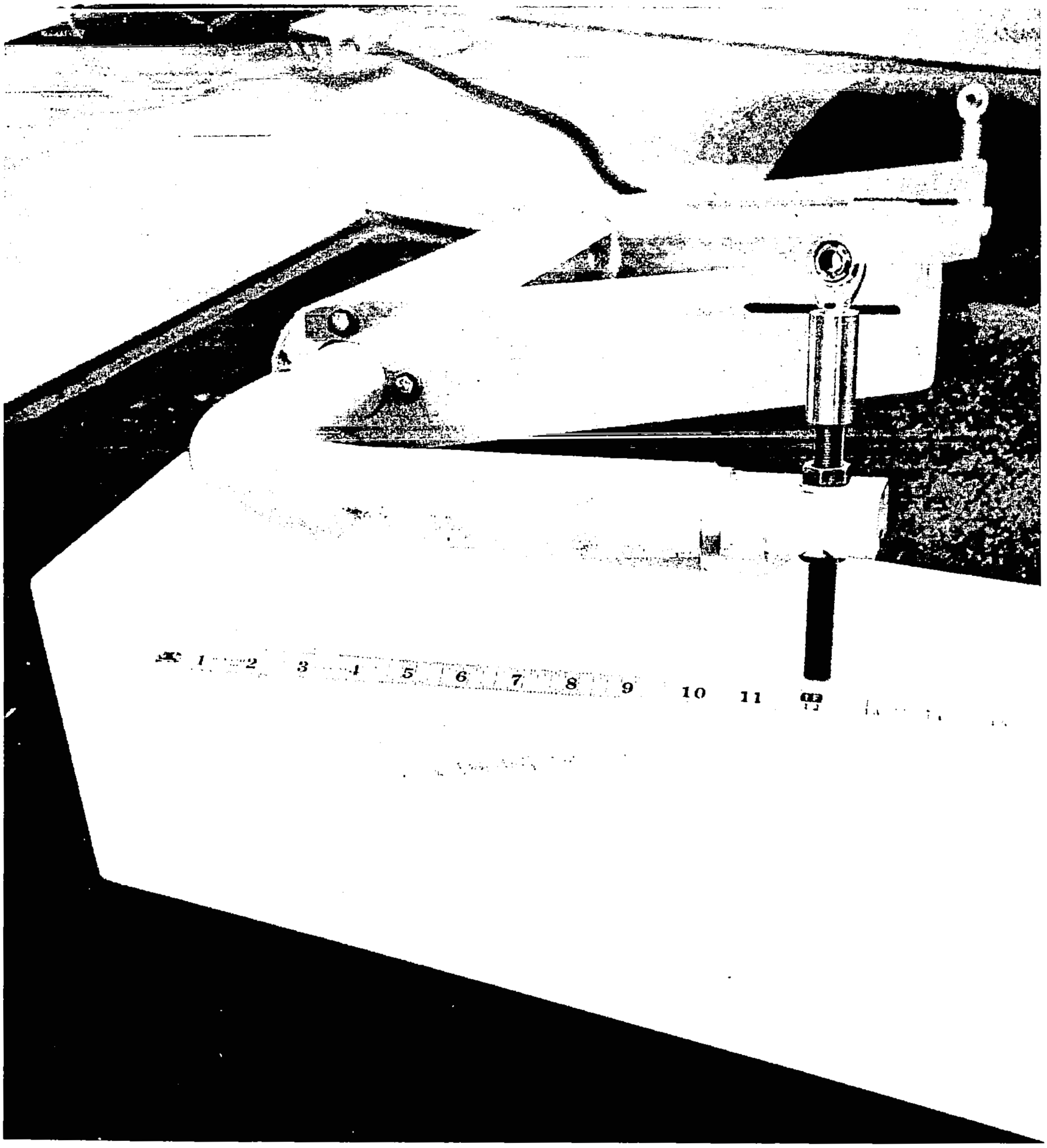


Fig. 2-14. Lower support bar of the whiffle tree

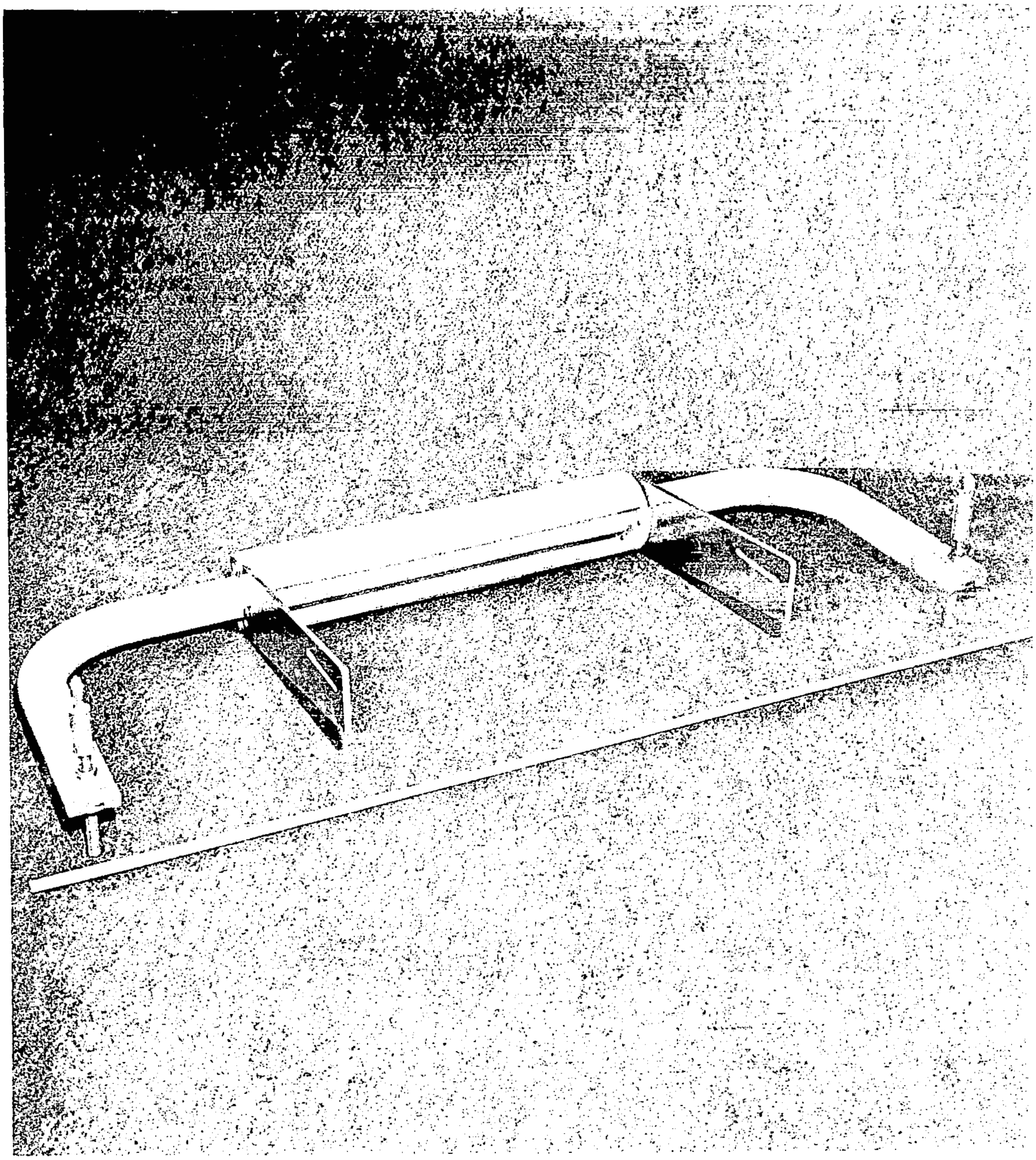


Fig. 2-15. Lower section of the whiffle tree

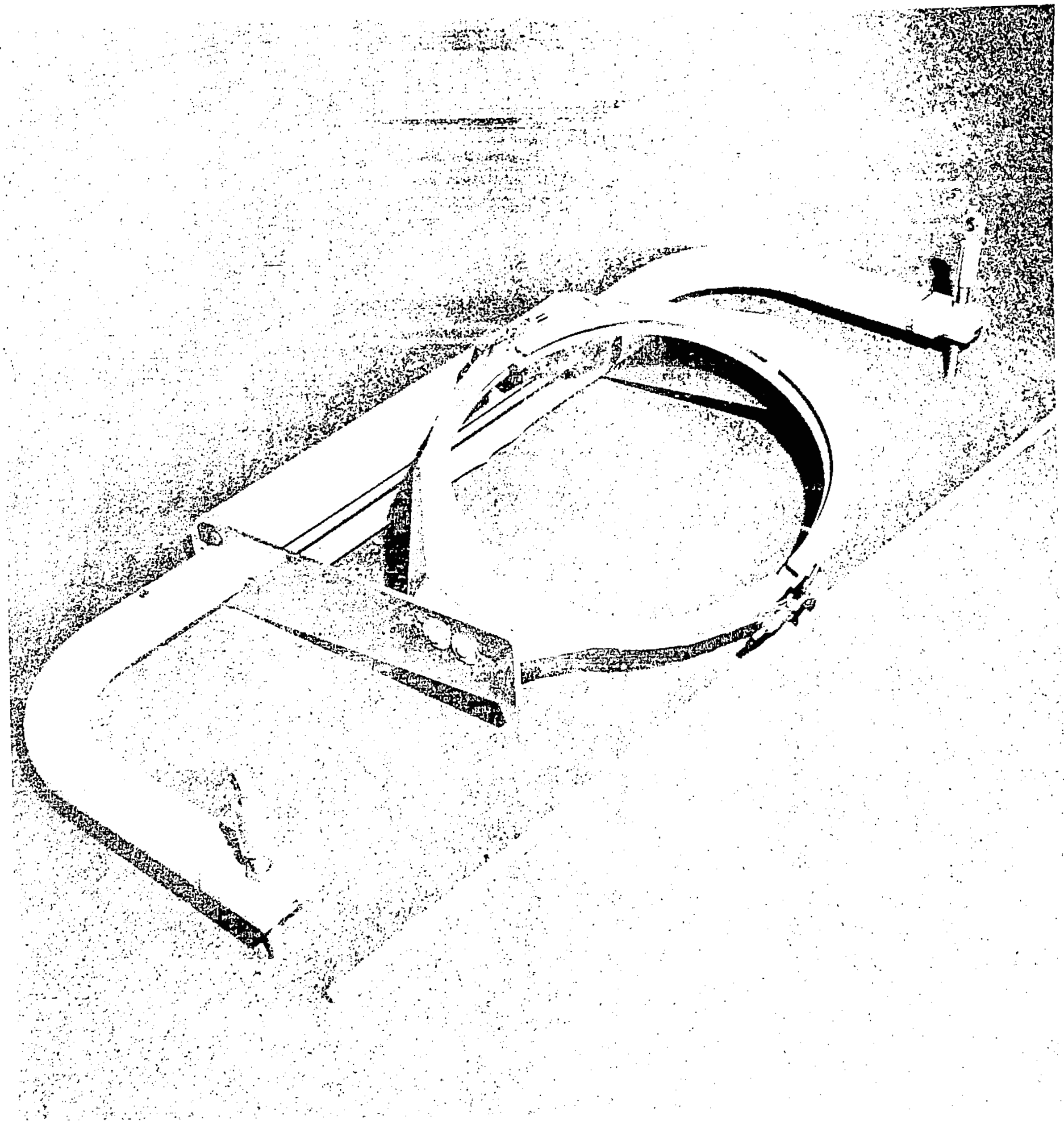


Fig. 2-16. Lower portion of the whiffle tree with the EX-1A mounting ring installed

Fig. 2-17. Waist joint piston for counterbalancing suit upper torso weight

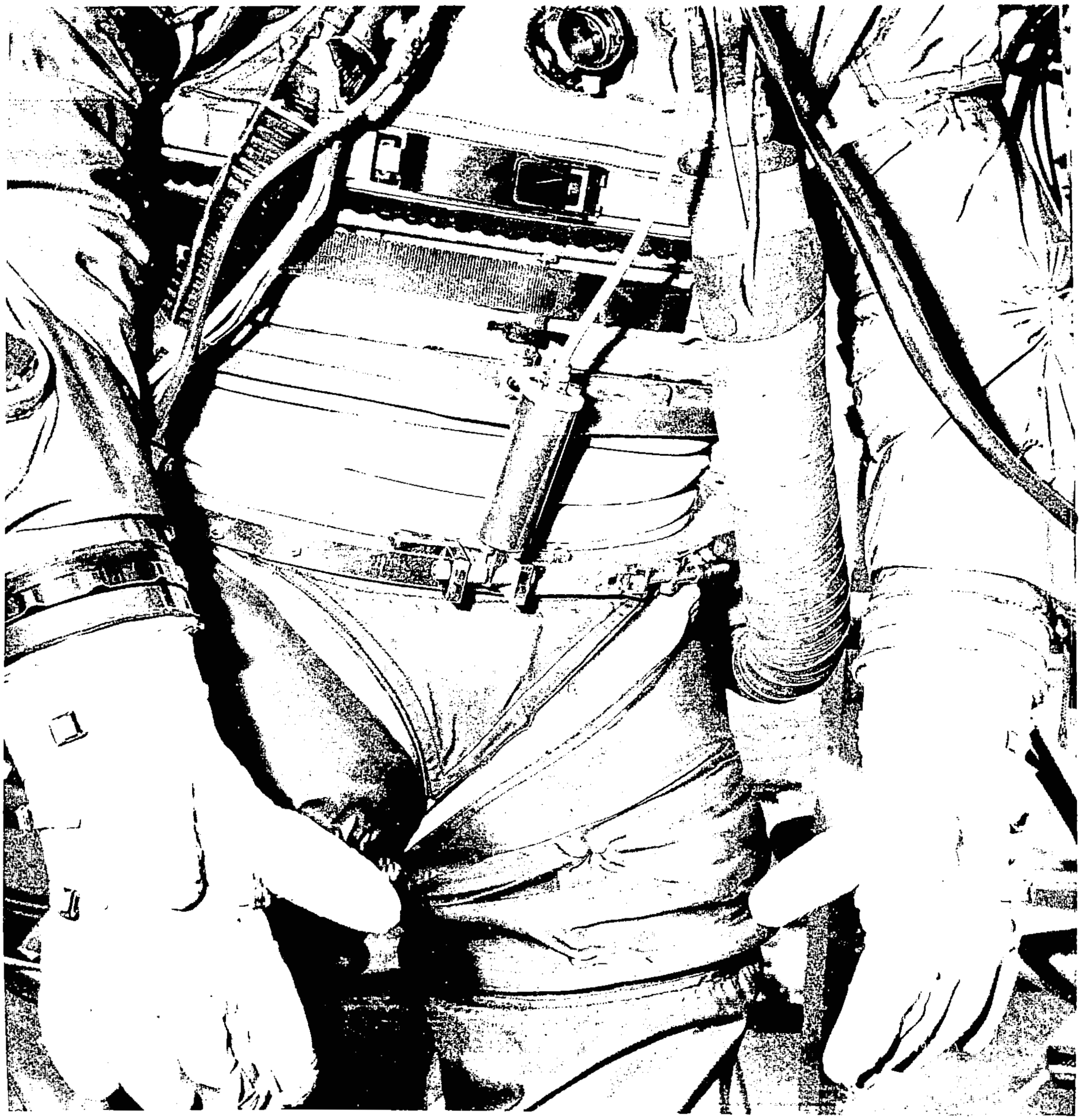


Fig. 2-18. Closeup of waist joint piston

BACKPACK FOR LOAD CARRYING

Two backpack loads were required for testing: 75 lb and 240 lb. Since the blow-by suspension system has only a single pickup cable, simulation of the backpack mass would have required a separate suspension system to handle the weight; therefore, mass was not simulated. The 1/6-g backpack weight and overturning moment to the subject was simulated. The backpack was made of several sheets of lead approximately 9 by 12 by 1/4 in. thick. The sheets were held in place by two bolts. The first sheet was fitted with 1-in. wide nylon webbing with quick disconnect snaps. Fig. 2-19 shows the backpack. Fig. 2-20 shows the simulated 240-lb pack attached to the subject's back. For a 240-lb backpack, a 40 lb load was attached to the subject's back. For a 75-lb backpack, a 12.5-lb load was attached to the subject's back.

LUNAR SOIL SIMULATION

Two types of lunar soil were simulated. Soil 1 is a dry coarse soil used in previous tests and described in NASA CR-1402 (ref. 1). This dry coarse soil possessed no cohesive properties. Soil 2 has increased cohesive properties. Soil 2 was selected based on preliminary examination of lunar samples from Apollo 11 as reported in Science in September 1969 (ref. 2). The properties for the lunar soil sample of Apollo 11 were reported to be

(1) Bulk density (loose), 1.36 g/cc

(2) Cohesion, 0.05 to 0.20 $lb/in.^2$

These two parameters were considered the prime goals of the soil simulations, and all other properties were subordinated. The lunar soil possessed the ability to stand on vertical slopes and to retain the detail of a deformed shape; the side walls of trenches dug with a scoop were smooth and sharp.

Based on the above properties, a casting sand was selected to meet those requirements. A sample of material was sent to an independent laboratory for analysis of its physical and mechanical properties. The results of this analysis is as follows:

(1) The material consists of light brown fine to medium grain sand with a trace of clay. Fig. 2-21 shows the distribution of grain size.

(2) The density of the sample was determined by allowing the sand to free fall into a 1/10-cu ft container. The test results indicate a density of 1.38 g/cc with a moisture content of 1.5 percent.

(3) The safe static bearing for a 2- to 3-in. thick soil layer for 5.4- and 8.0-percent moisture content was 1000 lb/sq ft. Consolidation test results are shown in fig. 2-22.

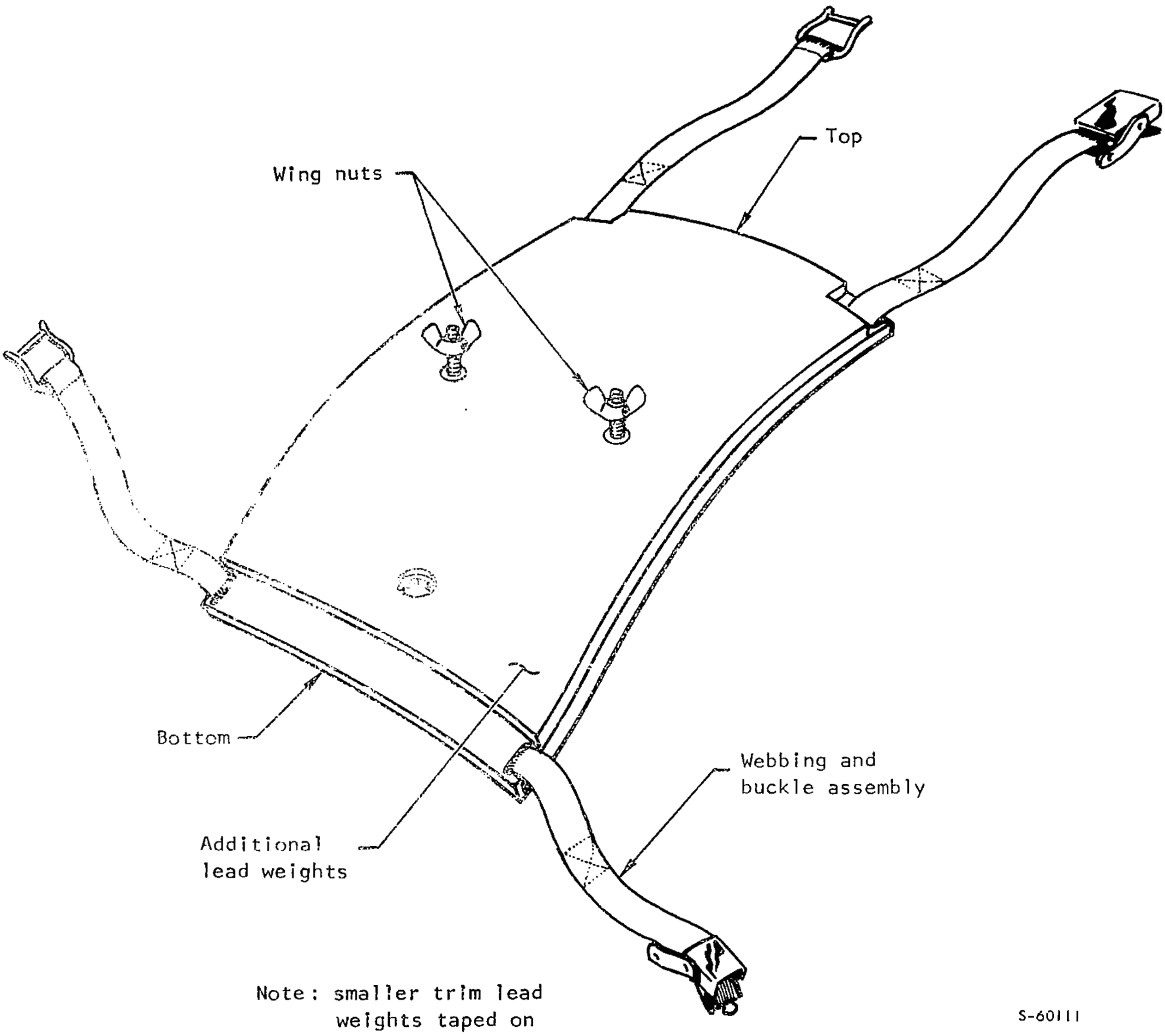


Fig. 2-19. EX-1A suit test backpack

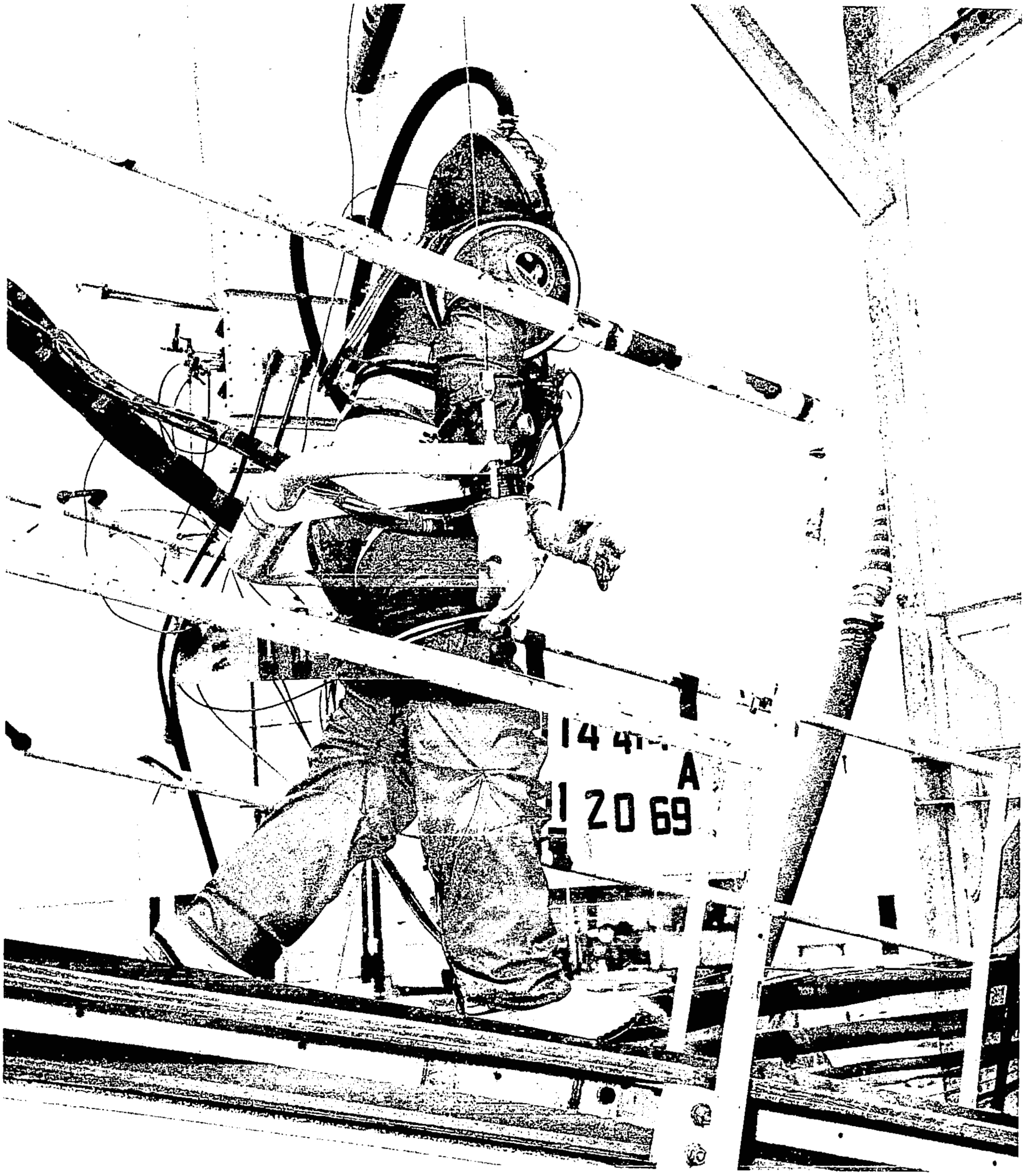


Fig. 2-20. Subject carrying a simulated 240-lb backpack

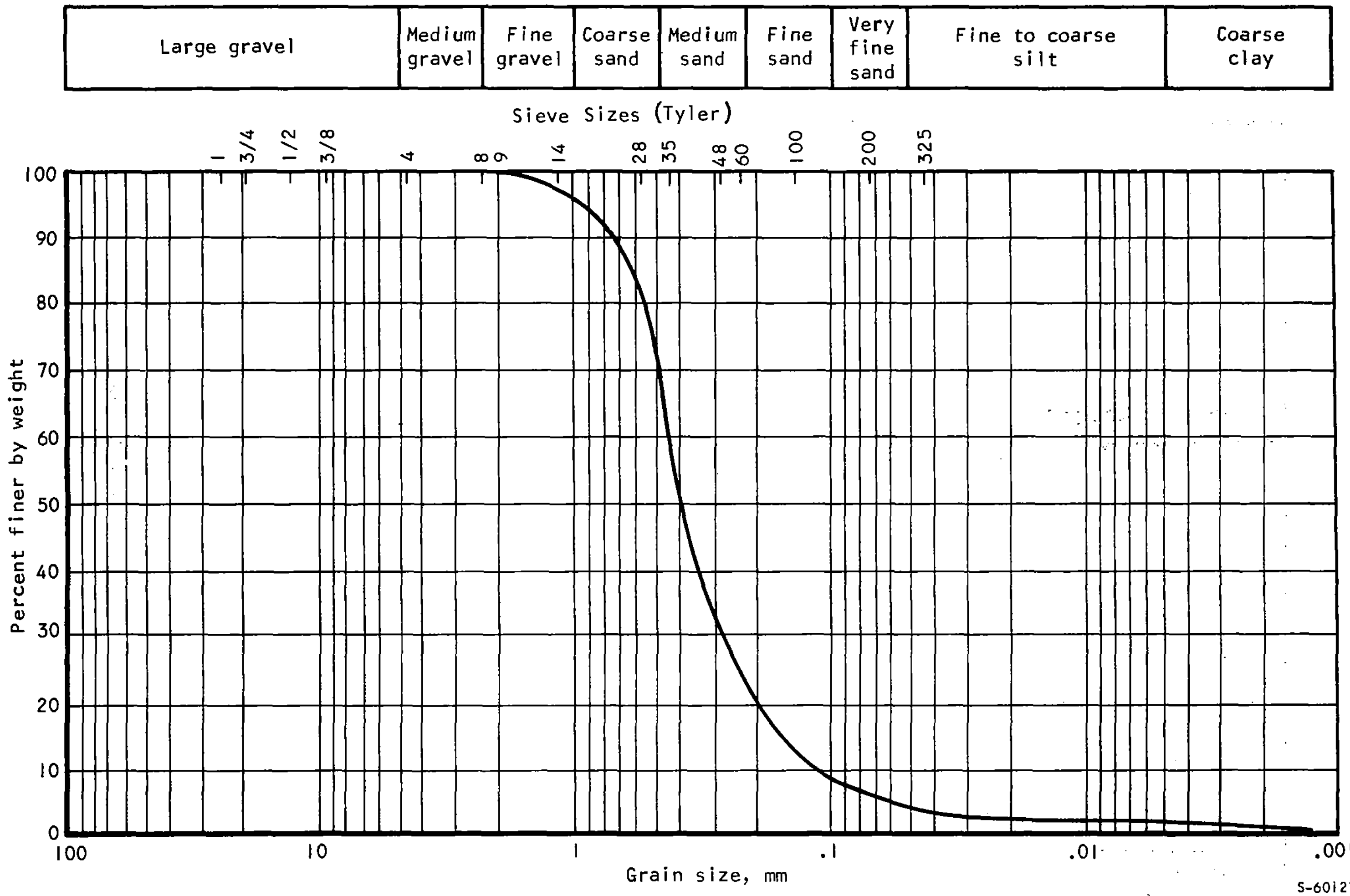


Fig. 2-21. Mechanical analysis curve of Apollo 11 soil simulant

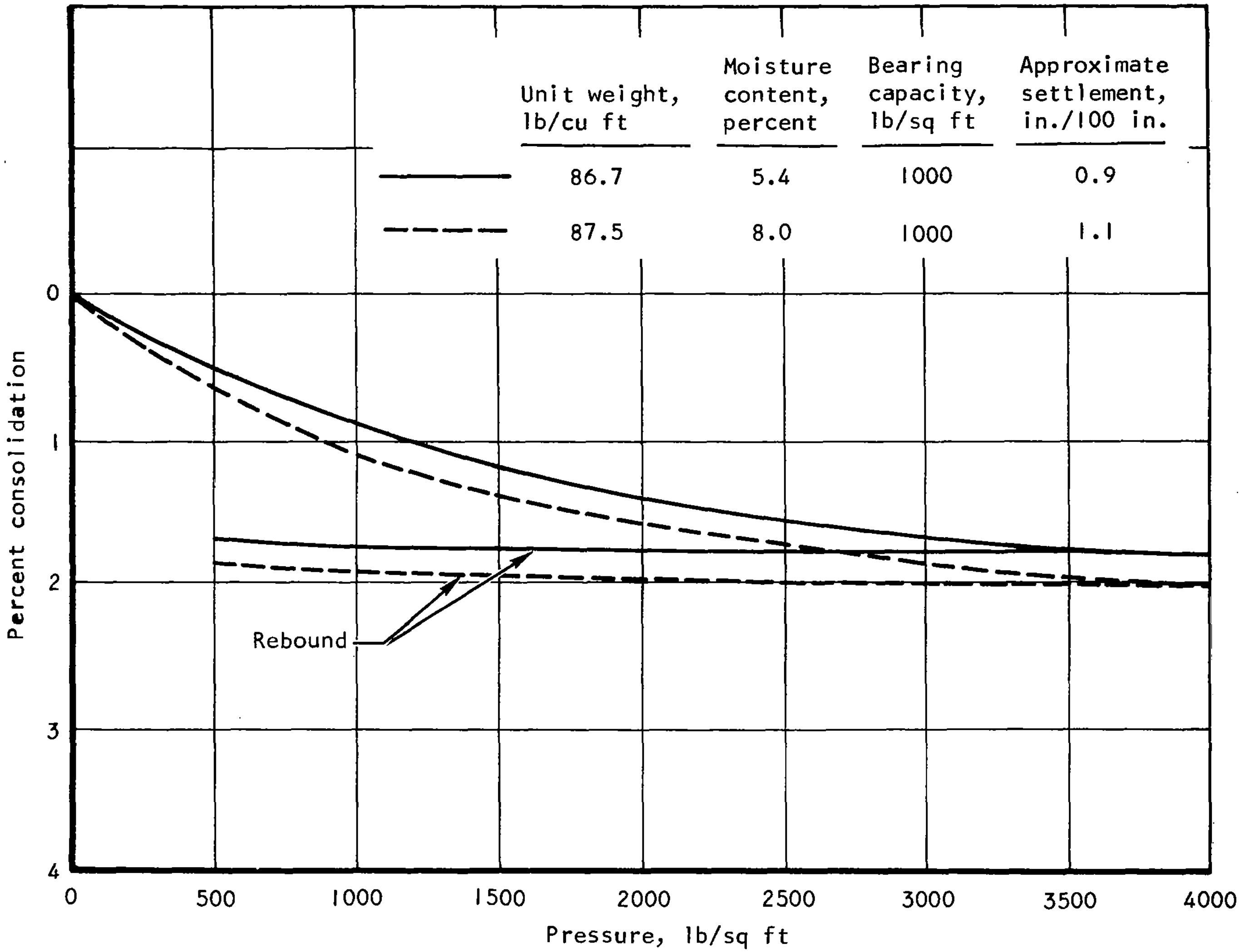


Fig. 2-22. Consolidation test of Apollo 11 soil simulant

(4) The average angle of repose of 34° was determined by dropping the sand from a height of 18 in. The sample used for this test contained 1.5 percent moisture by weight of dry material.

(5) Direct shear testing (fig. 2-23) was performed on samples remolded to 1.39 g/cc and 1.40 g/cc for 5.4- and 8.0-percent moisture content. The angles of internal friction and cohesive values were determined under a surcharge of 260, 520, and 1040 lb/sq ft. For a 5.4-percent moisture content, the angle of internal friction was 22° and cohesion was 0.139 psi. For a 8.0-percent moisture content, the angle of internal friction was 24° and cohesion was 0.0 psi.

Assuming a straight-line relationship between moisture content and cohesion, a graph (fig. 2-24) was made based on the two data points of the report. The arithmetic average of moisture content measured during the test was 6.3 percent. From the graph, the average cohesion of the soil corresponds to 0.091 psi. Soil 2 compared favorably with the properties of cohesion and density reported for Apollo 11.

Each day following the metabolic test, samples of Soil 2 were taken and the moisture content was measured and recorded. Water was added as necessary. The moisture content of the soil was easily controlled between 5 to 7 percent. These analyses were necessary to maintain the validity of the lunar soil simulation.

LUNAR PULL CART

A lunar pull/push cart was designed for evaluation as a load carrying device. The cart was suspended at 1/6 g and was movable fore and aft on the treadmill surface. Fig. 2-25 shows the lunar cart and suspension rig on a 15° descending slope.

The pull cart consists of an aluminum frame with 20-in. diameter bicycle wheels. The frame is 31.5 in. wide by 30.5 in. long. The frame is approximately 1 in. below the center line of the wheels and clears the ground by 6 in. Two movable weight platforms were secured between the wheels. Flat sheets of lead were bolted to the platforms to provide cart weights of 165 and 235 lb. The platforms were adjustable fore and aft to keep the entire cart balanced. Two removable arms with hand holds were attached to the front of the cart for the suited subjects to grasp. Fig. 2-26 shows the basic cart without weights and arms. Due to the pressurized glove design, the subject could not maintain his grip on the cart handholds for longer than 3 min. Fig. 2-27 shows the lunar cart on a 0° slope. The bicycle wheel rims were covered with 4-in. wide aluminum strips to give a lower soil bearing load pressure.

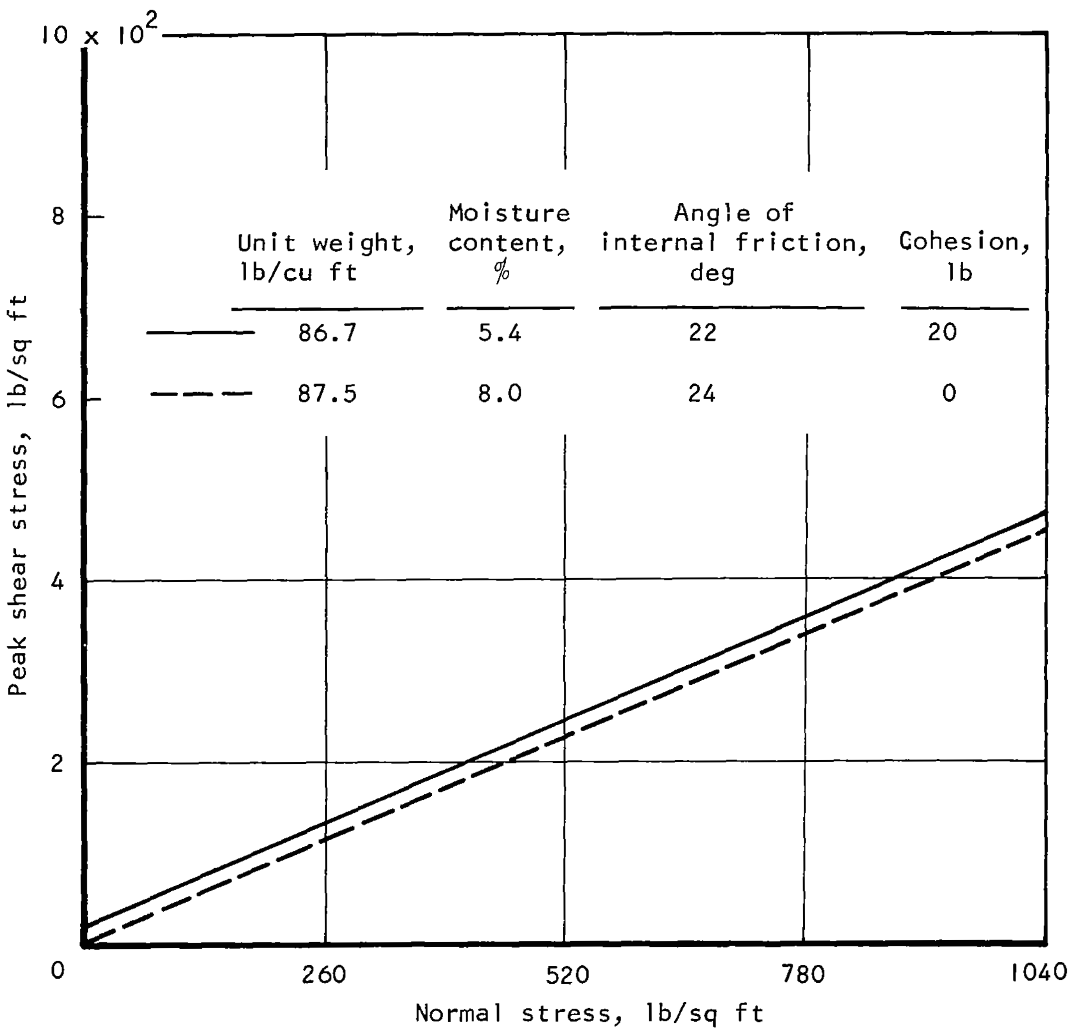


Fig. 2-23. Direct shear test of Apollo II soil simulant

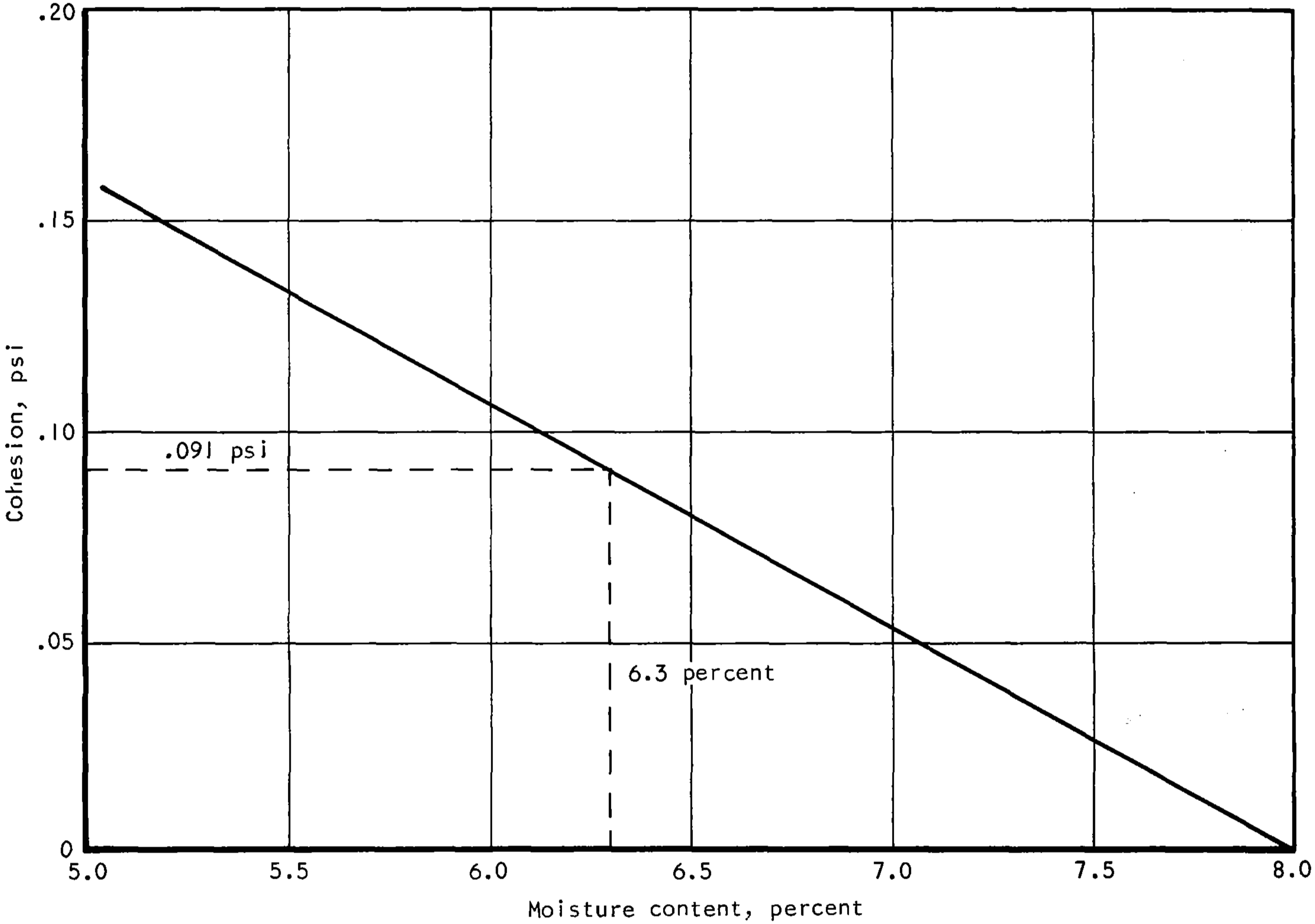


Fig. 2-24. Cohesion of the Apollo 11 soil simulant as a function of moisture content

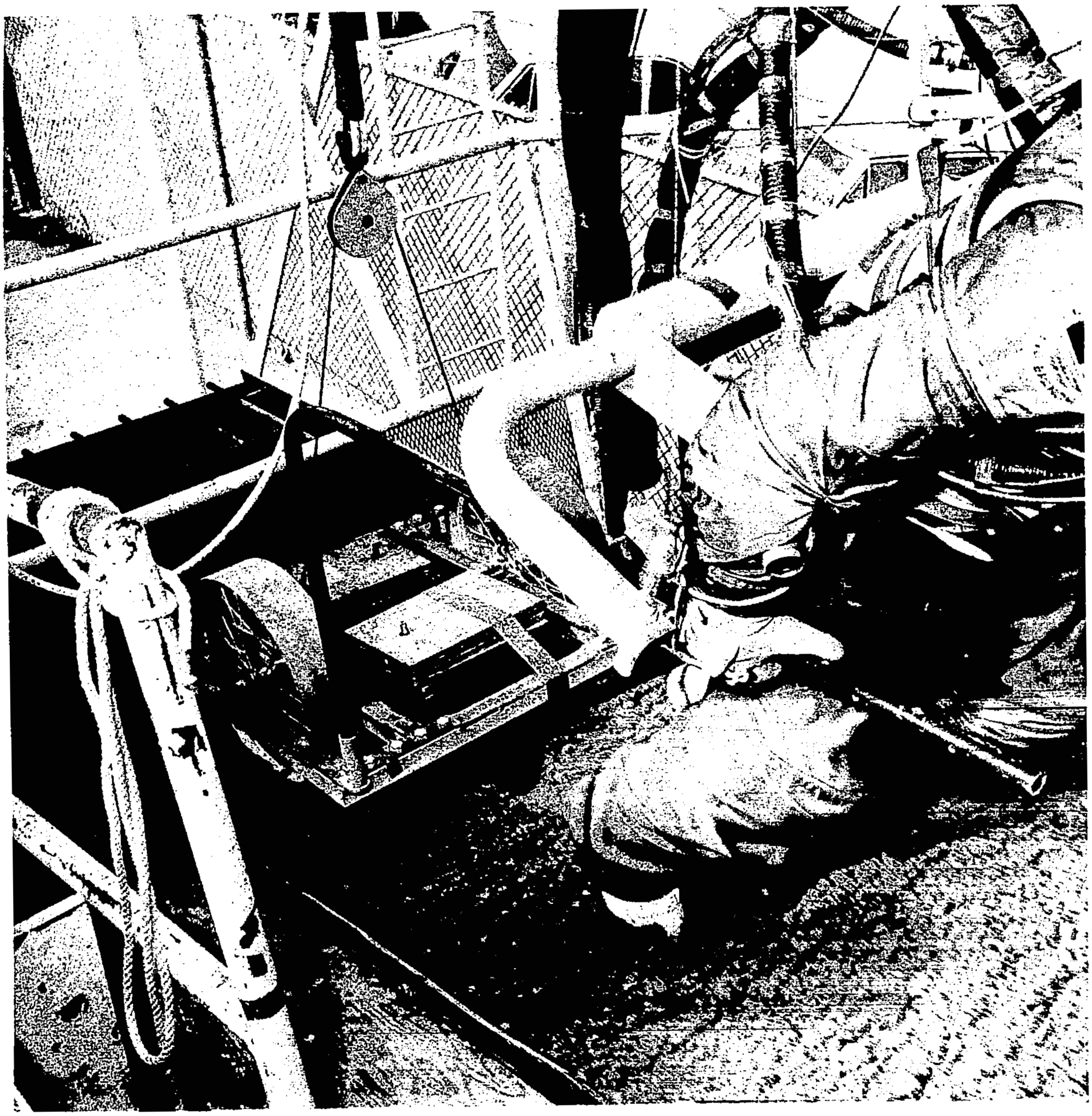


Fig. 2-25. Lunar cart being pulled down a 15° slope

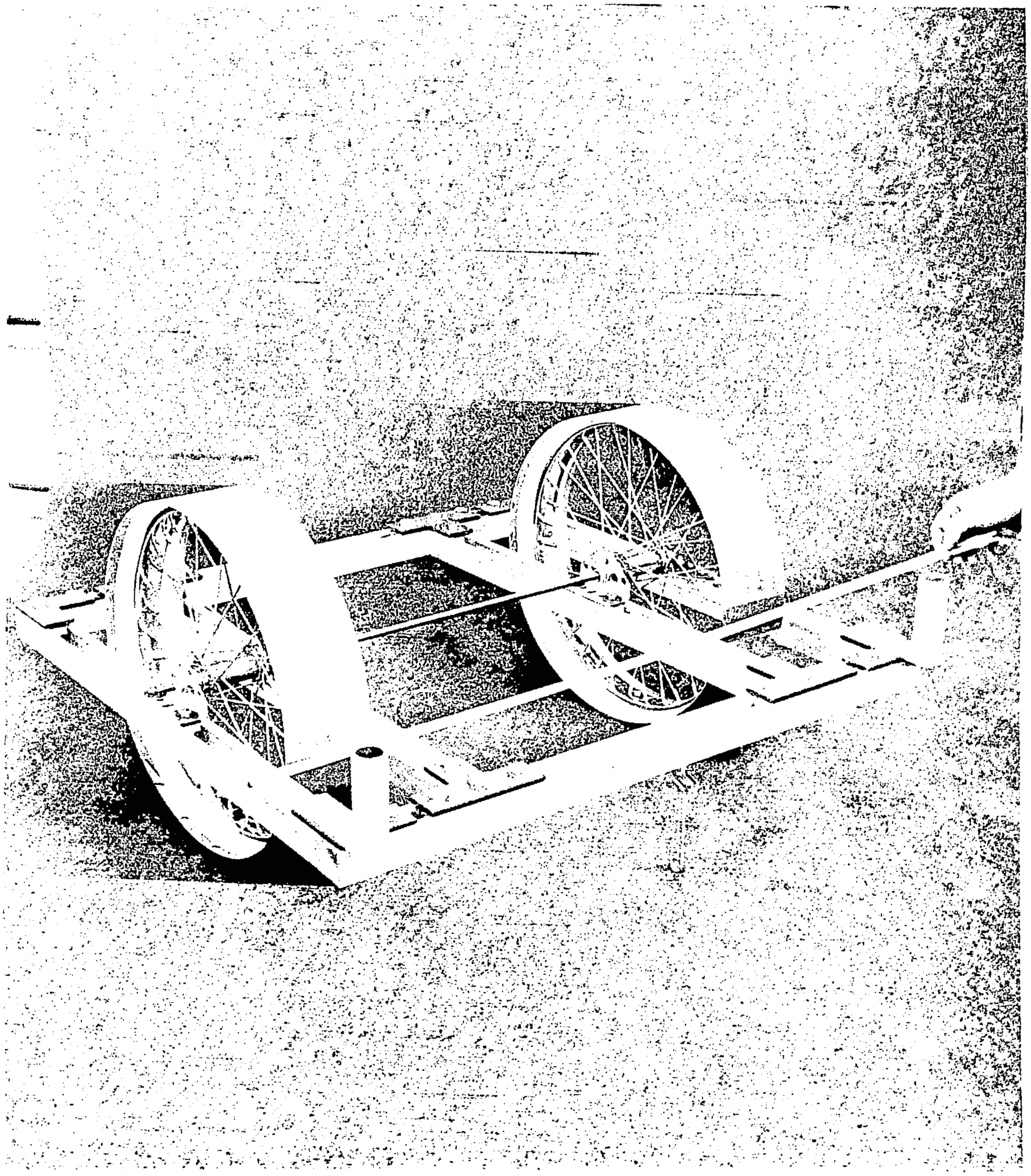


Fig. 2-26. Basic cart without weights and draw bars

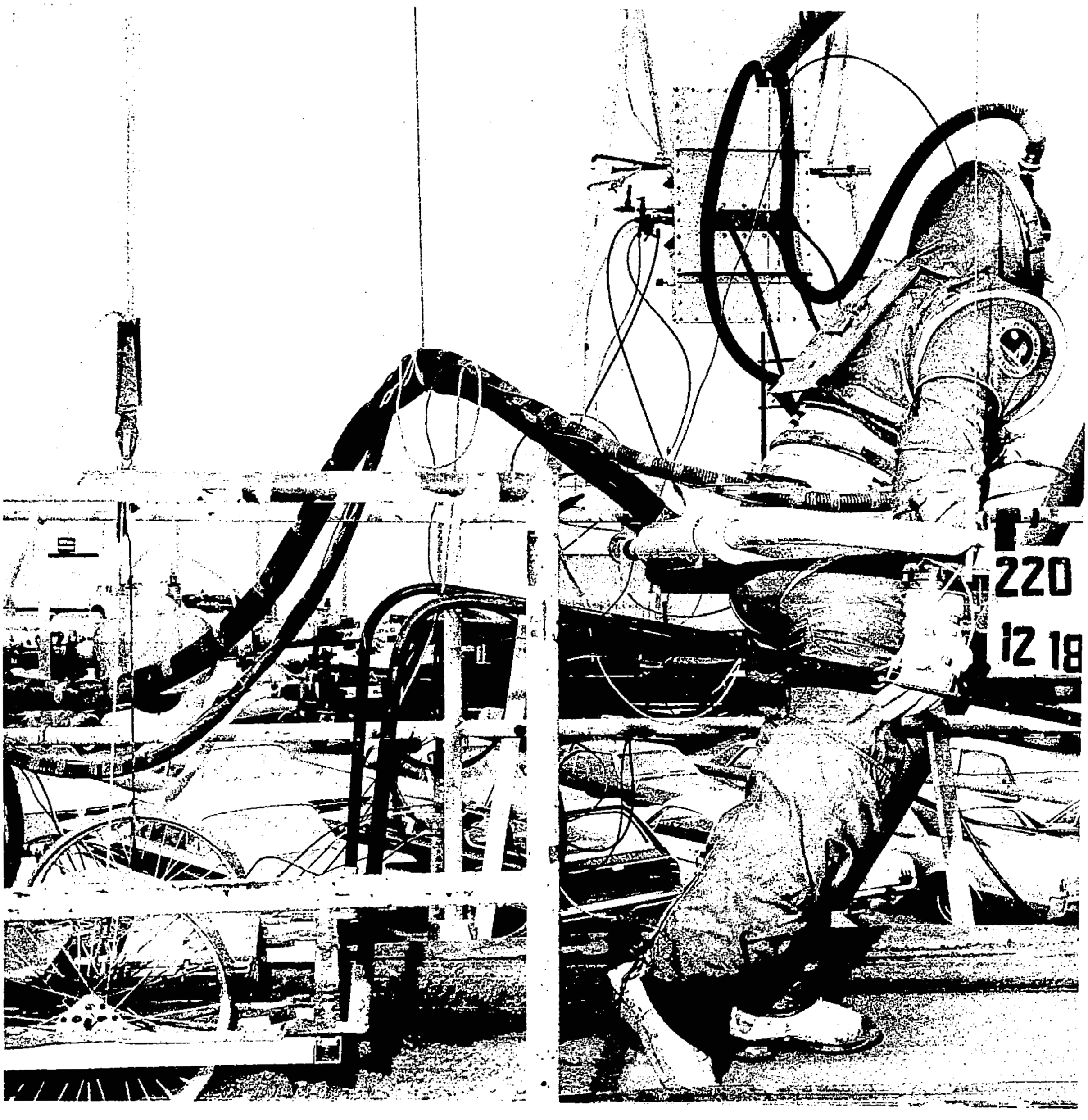


Fig. 2-27. Lunar cart being drawn on a 0^0 slope

Pull Cart Suspension

The cart was suspended at 1/6 g by means of a 1/2-in.-diameter bungee cord. Fig. 2-28 shows the cart suspension rig and Table 2-2 shows the degrees of freedom. The bungee cord is looped through two twin pulley blocks set up to provide a 2-strand or 4-strand block and tackle pickup. The upper block is attached to an air bearing yoke assembly for fore and aft motion. The air bearing yoke assembly rides on the same beam that supports the subject.

TABLE 2-2.-- LUNAR CART SUSPENSION SYSTEM DEGREES OF FREEDOM

Component	Type of freedom	Degrees of freedom
Pulley and cable pickup	Roll	1
Shackles and wheel bearings	Pitch	1
Bungee cord and wheels	Yaw	1
Yoke (with air pads)	Fore and aft	1
Beam (pivot and air pads)	Lateral	1
Bungee cord	Vertical	1
Total degrees of freedom		6

The lower block is attached to a pulley which can travel left and right on a steel cable shackled to the cart axle. This allows the cart to rotate in the axis over an uneven surface. The two mounting shackles and wheel bearings allow rotation around the pitch axis of the cart. Rotation about the yaw axis is accomplished by the pivoting of the cart about one of the wheels and by the low torsional resistance of the bungee cord. Up and down motion of the cart is through the bungee cord spring. Side to side motion is dependent on where the subject positions the upper pivoted support beam.

The bungee cord used for the cart suspension is composed of strands of rubber encased in a woven fabric outer covering. Spring rate tests were conducted on a 1/2-in.-diameter bungee cord. The results of the tests are plotted in fig. 2-29.

The lower the bungee cord spring rate, the closer the cart suspension simulates a constant lifting force. As shown in fig. 2-29, a 68-lb load force on a 1/2-in. bungee cord will result in a deflection spring rate of 14 lb/ft. An increased load on the cord will not significantly change the spring rate.

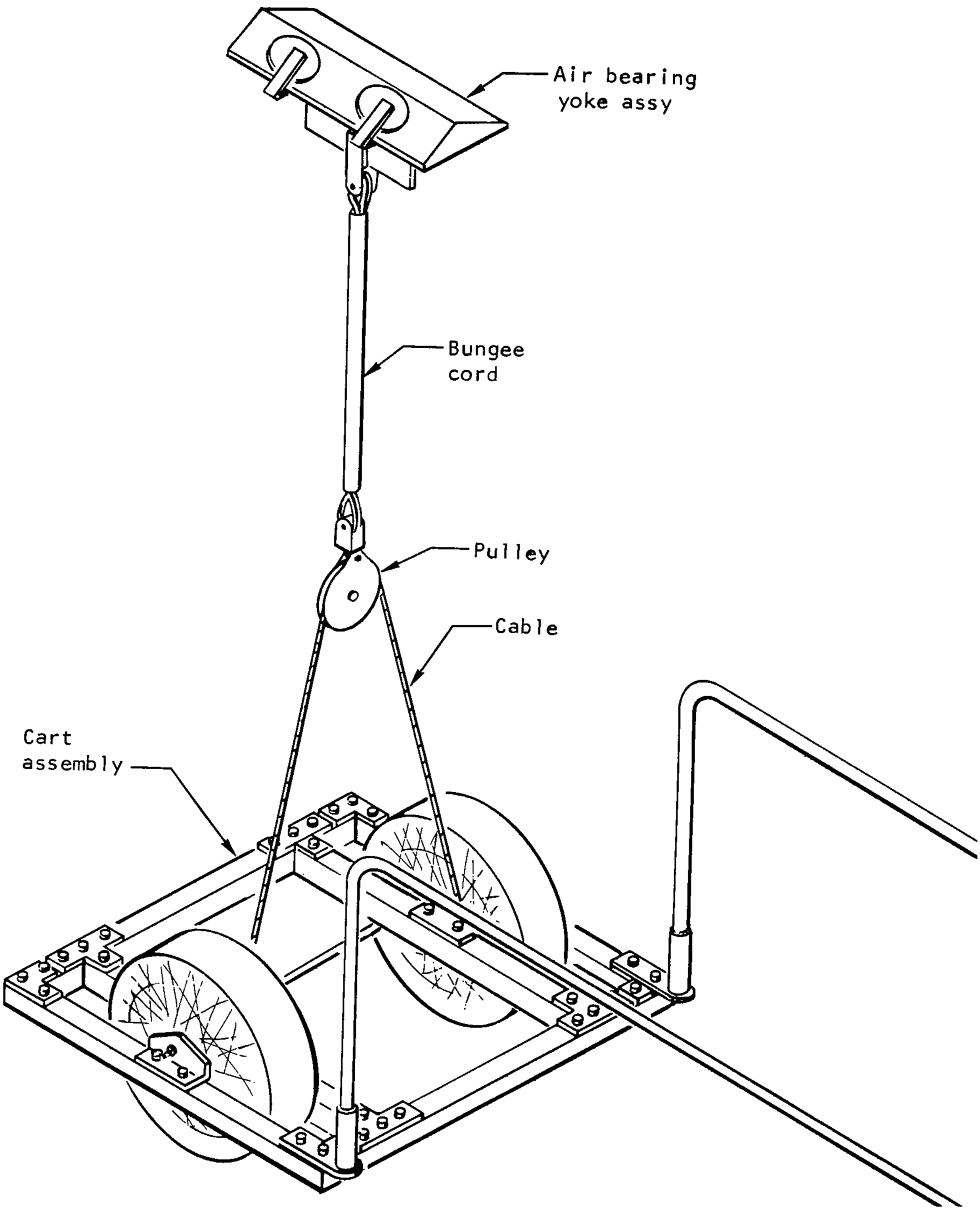


Fig. 2-28. Cart suspension system

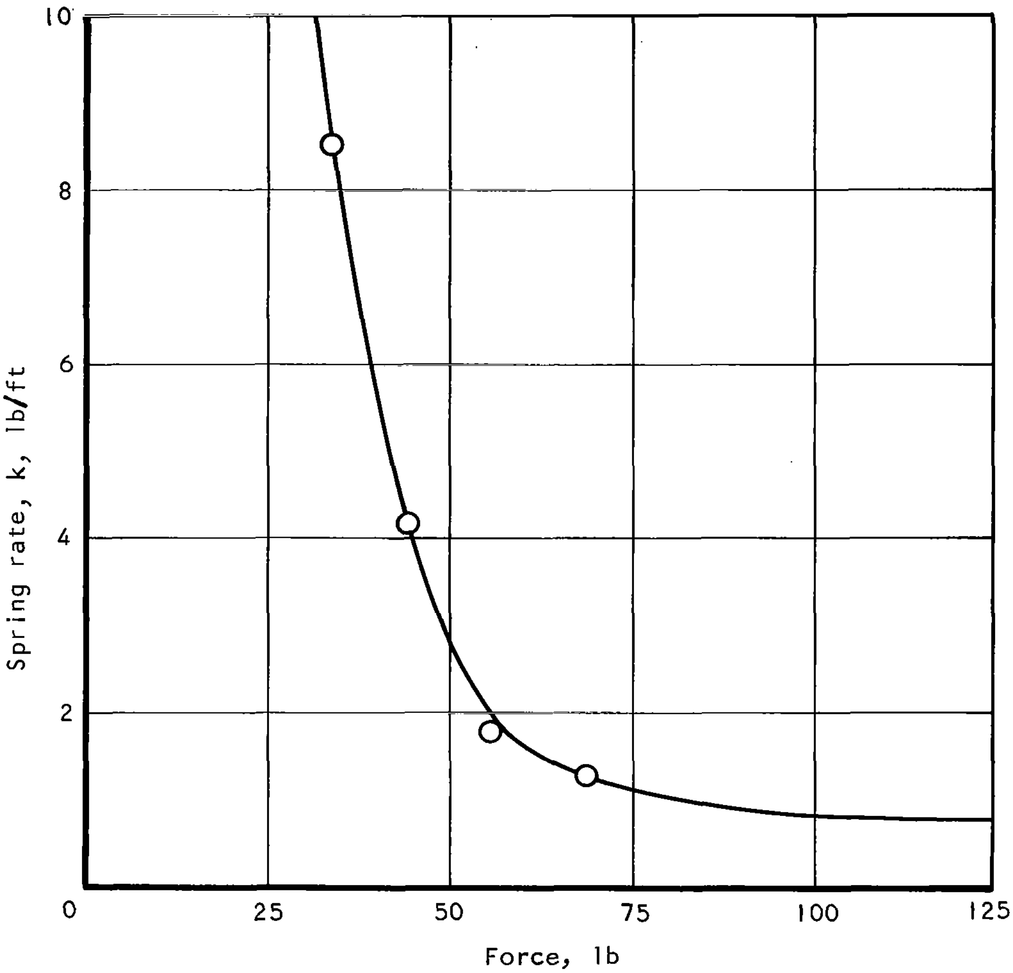


Fig. 2-29. Spring rate versus lifting force for a 1/2-in. diameter bungee cord

For a 165-lb cart, the suspended weight is 137.5 lb (165 x 5/6), and for a 325-lb cart, the suspended weight is 271-lb (325 x 5/6). Fig. 2-29 shows that the use of two bungee cords for the 165-lb cart results in a tension/cord of 68.8 lb. For the 325-lb cart, four bungee cords results in a tension/cord of 65.3 lb. This results in spring rates of approximately 14 lb/ft for the bungee cords.

The tests were conducted with a 2-cord bungee suspension for the 165-cart, and a 4-cord bungee suspension for the 325-lb cart. A block and tackle system was used to adjust the tension in the bungee cords.

The change in lifting force for a ±6-in. deflection is ±14 lb for the 2-cord suspension and ±28 lb for the 4-cord suspension. No dynamic response tests were performed on the lunar cart suspension system. The vertical excursion of the cart during the tests was approximately ±1 in.

The estimated change in lifting force for a ±1 in. vertical cart excursion is ±2.3 lb for the 2-cord suspension and ±4.6 lb for the 4-cord suspension.

Adjustment for both the 165-lb and 325-lb carts was accomplished by loading lead weights onto the cart until the 5/6-g cart weight was reached. The tension in the bungee cord cables was increased by pulling on the bungee cord block and tackle system until the cart was suspended about an inch off the treadmill surface. The additional 1/6-g cart lead weights were added on to the cart to complete simulated cart mass. The cart was then balanced by shifting the lead weights fore and aft on the cart so that the cart handles were level.

Lunar Cart Pull Force Tests

During the pull force tests, lunar cart mass was not simulated, only the tread load. For a 165-lb cart, the tread load at 1/6 g would be 27.5 lb. The actual empty cart weight was 34 lb without handles. The lunar cart pull force tests were run at tread loads of 34 and 54 lb.

The pull force was measured with a force gage attached to the lunar cart. The treadmill speed was adjusted to the desired velocity, and the force reading was observed at steady-state conditions. The independent variables were treadmill velocity, treadmill angle, and surface. The data is presented in fig. 2-30 and table 2-3.

Preliminary pull force tests indicated that 4-in.-wide wheel rims result in lower pull forces than 1.6-in.-wide wheel rims under similar conditions. The cart wheels were assembled with 4-in.-wide wheel rims.

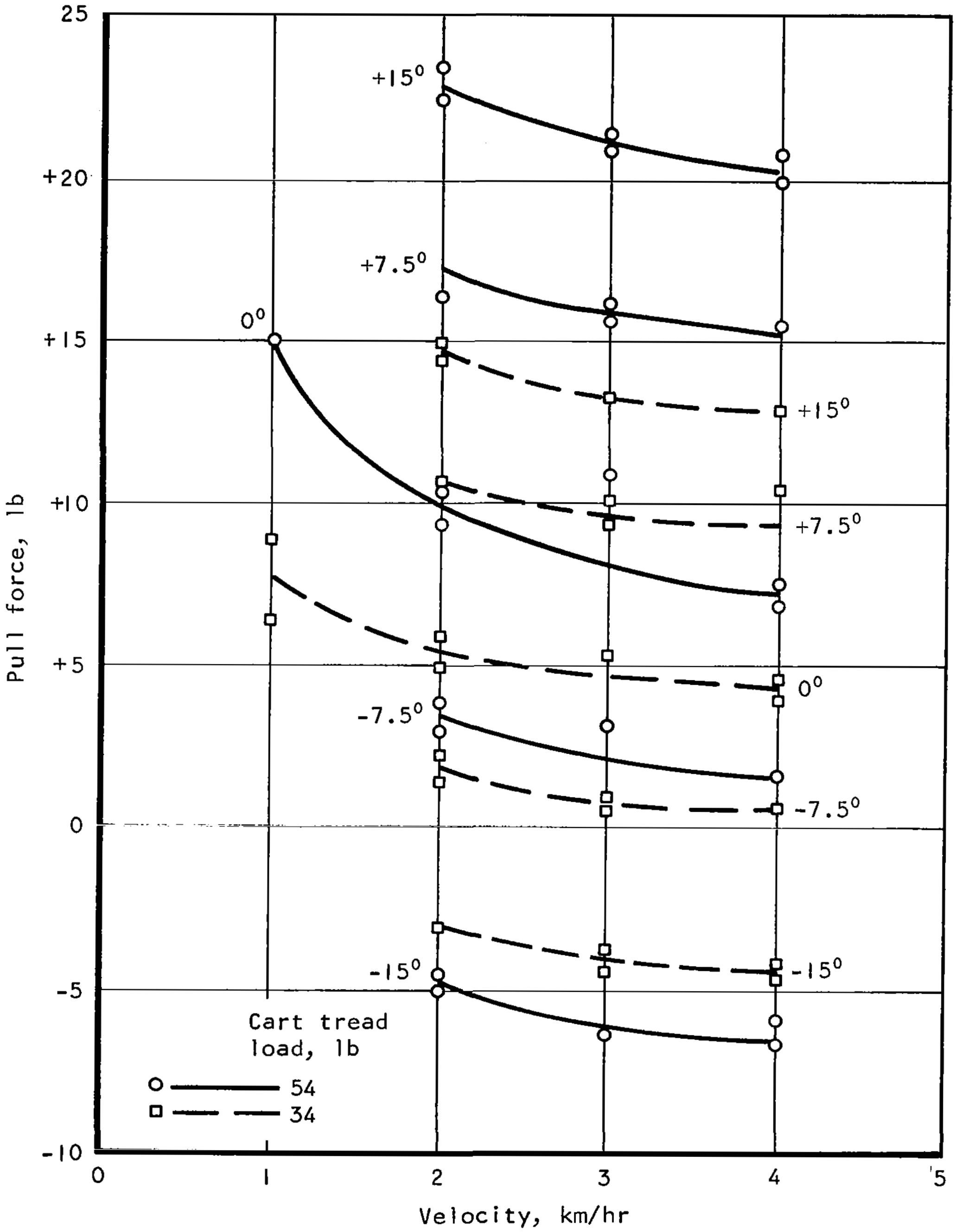


Fig. 2-30. Force required to pull a cart in simulated lunar gravity

TABLE 2-3.-- LUNAR CART PULL TESTS

Track width, in.	Cart weight, lb	Slope $\theta = 0^{\circ}$ V = 2 km/hr		Slope $\theta = 0^{\circ}$ V = 4 km/hr	
		Pull force, lb	Soil type	Pull force, lb	Soil type
1.6	34	1.0	Hard	1.0	Hard
1.6	34	7.0	Soil 1[a]	7.0	Soil 1
1.6	54	14.0	Soil 1	12.0	Soil 1
4.0	34	1.0	Hard	1.0	Hard
4.0	34	4.0	Soil 1	4.5	Soil 1
4.0	34	5 to 6	Soil 2[b]	4 to 4.5	Soil 2
4.0	54	11.0	Soil 1	10.0	Soil 1
4.0	54	9.5 to 10.5	Soil 2	7 to 7.5	Soil 2

[a]Soil 1 is coarse lunar soil simulant
[b]Soil 2 is Apollo 11 soil simulant

The forces acting on the lunar cart at a slope θ are shown in Figure 2-31. The dynamic forces acting on the cart can be expressed as follows:

$$F_{pull\ force} = F_{friction} \pm F_{cart} \sin\theta \qquad \text{eq. (2-1)}$$

where $F_{pull\ force}$ = Total cart pull force, lb

$F_{friction}$ = Frictional, inertial, velocity, and soil forces acting on cart, lb

F_{cart} = Cart weight, lb

θ = Slope, deg

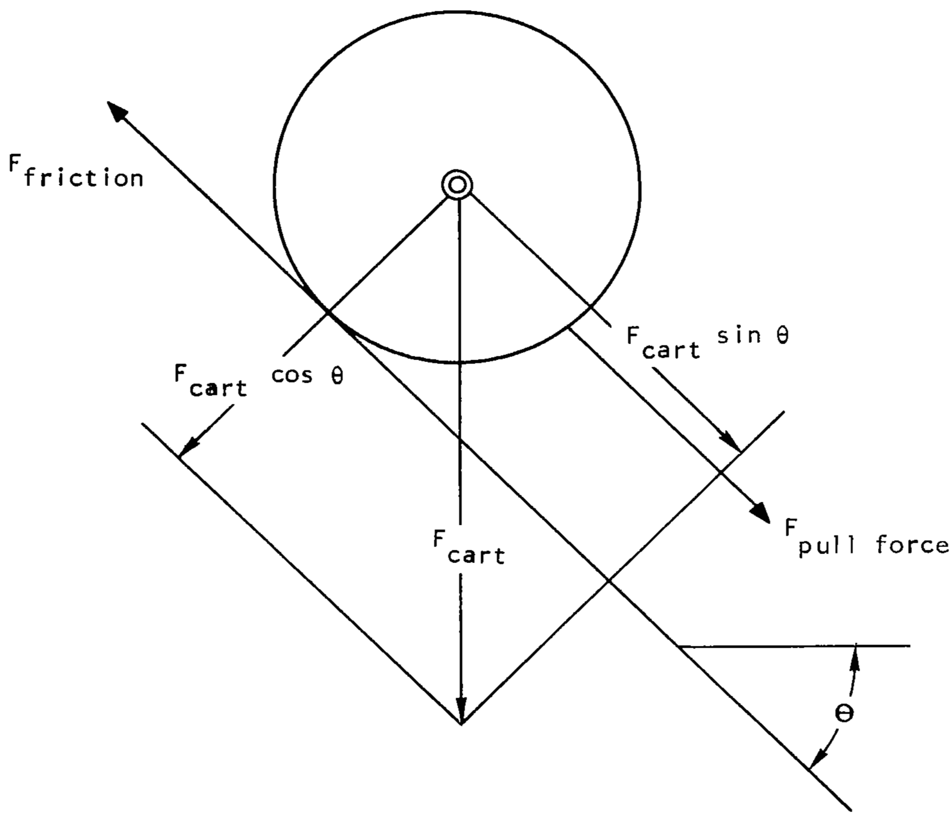


Fig. 2-31. Forces for a wheel on a slope

The pull force is proportional to frictional, inertial, and soil forces and a sine component of the carts normal loading force on the soil. Eq. (2-1) lumps the relatively constant part of the cart pull forces into a single parameter. The slope effect is shown as an additive or subtractive component of the cart weight. For a level surface, the slope effect component $F_{cart} \sin \theta$ equals 0 because θ equals 0.

Pull forces measured on the lunar cart are shown in Table 2-3 for $\theta = 0^0$. If the cart pull force is as expressed in eq. (2-1), then subtracting the 0^0 slope data from the $\pm 7.5^0$ slope data and from the $\pm 15^0$ slope data should yield only the $F_{cart} \sin \theta$ component of the cart's weight. For a 34-lb cart the $\sin \theta$ component should be 4.4 lb and 7.0 lb for 7.5^0 and 15^0 slopes, respectively. For a 54-lb cart the $\sin \theta$ component should be 8.8 lb and 14.0 lb for 7.5^0 and 15^0 slopes, respectively. The average difference between the 0^0 slope data and both 7.5^0 and 15^0 slope data is shown in table 2-4 (the average difference equals $F_{cart} \sin \theta$).

TABLE 2-4.-- COMPARISON OF CART PULL FORCES

Slope, θ, deg	Force	$F_{cart} \sin \theta$	
		$F_{cart} = 34$ lb	$F_{cart} = 54$ lb
7.5	Actual	4.3 lb	9.0 lb
	Theoretical	4.4 lb	8.8 lb
15	Actual	6.4 lb	13.7 lb
	Theoretical	7.0 lb	14.0 lb

The correlation between the average actual data yields only a 0.6 lb maximum difference between theoretical and actual. This also would say that the $F_{friction}$ part of eq. (2-1) is relatively constant over a velocity range of 2 km/hr to 4 km/hr.

METABOLIC RATE ANALYZER SYSTEM

Metabolic Backpack Design

The respirometer and gas analyzers were incorporated into a backpack to improve overall instrumentation response time by reducing the distance between the metabolic instrumentation and the subjects to a minimum. The gas analyzer backpack also reduces the hoses which tend to encumber the subjects. The weight of the metabolic backpack was to be part of the simulated backpack weight. It was found during checkout tests that the CO_2 sensors were sensitive to shock and vibration and could not be placed on the subject. Therefore the backpack was mounted on the bungee shock cord adjacent to the subject.

The backpack was 23.5 in. high by 7.5 in. deep by 13.5 in. wide and weighed 43 lb. The pack is shown in fig. 2-32. The backpack is constructed of aluminum sheet with 1 by 1 by 1/8 in. angle-aluminum stiffeners. The pack consists of a rectangular box with a flat cover. The cover is made of aluminum sheet with stiffeners and is bolted to the bottom half. An O-ring seal on the bottom half acts as a pressure seal. Electrical connectors are positioned in the center of the cover. Respirometer external connections are made at the top of the pack.

Calibration connections are on the side of the pack. The pack has been proof tested to 10 psig without damage and leak tested at 5.0 psig. Fig. 2-33 is a photograph of the subject during a -15^{0} slope, soil 1 test and shows the backpack with hoses to the subject.

Metabolic Rate Analyzer System Operation

The metabolic rate analyzer system is shown schematically in fig. 2-34. The measuring system consists of a modified Franz-Mueller respirometer, a Beckman LB-1 infrared carbon dioxide sensor, a Technology Incorporated polarographic sensor, and polarographic sensor, and sensors to measure temperature and pressure of the expired air as it moves from the one-way valve assembly and tubing at the rear of the helmet into the respirometer for measurement of gas volume. The gas then moves into the buffer volume of the backpack and is ducted to the pressure suit through the rear of the helmet. The respirometer has been modified with electronic sensors that provide signals for volume recording and breath rate. The respirometer sampling circuit removes a proportional averaged expired breath sample over the entire breathing cycle.

Expired gas samples are ducted through an infrared carbon dioxide sensor and through the oxygen sensor. The expired gas sample is dumped into the backpack buffer volume. Inspired gas samples are taken directly from the inlet area of the low profile bifurcated mouthpiece and directed to both carbon dioxide and oxygen sensors and finally are vented overboard to the atmosphere.

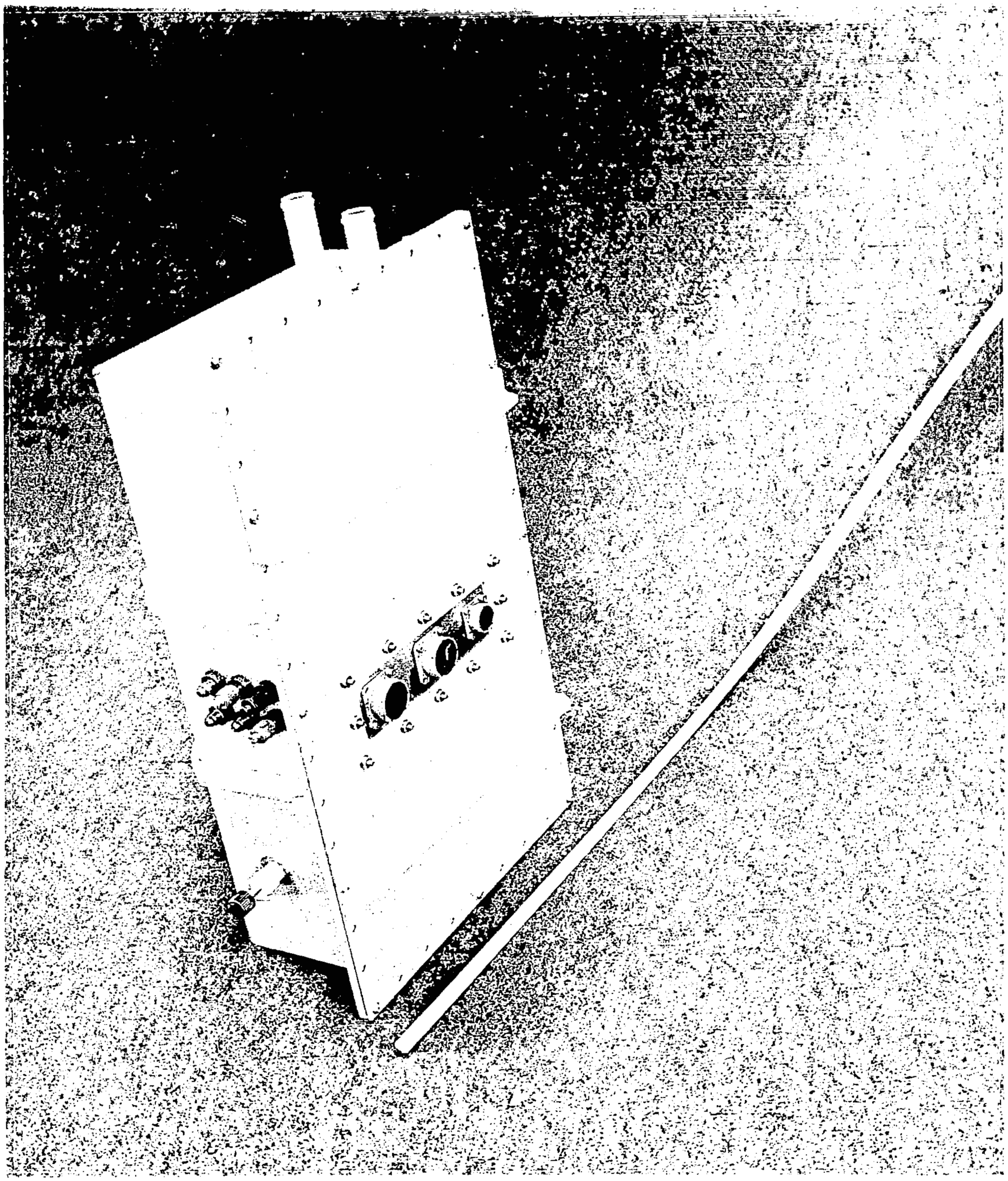


Fig. 2-32. External view of the metabolic analyzer package

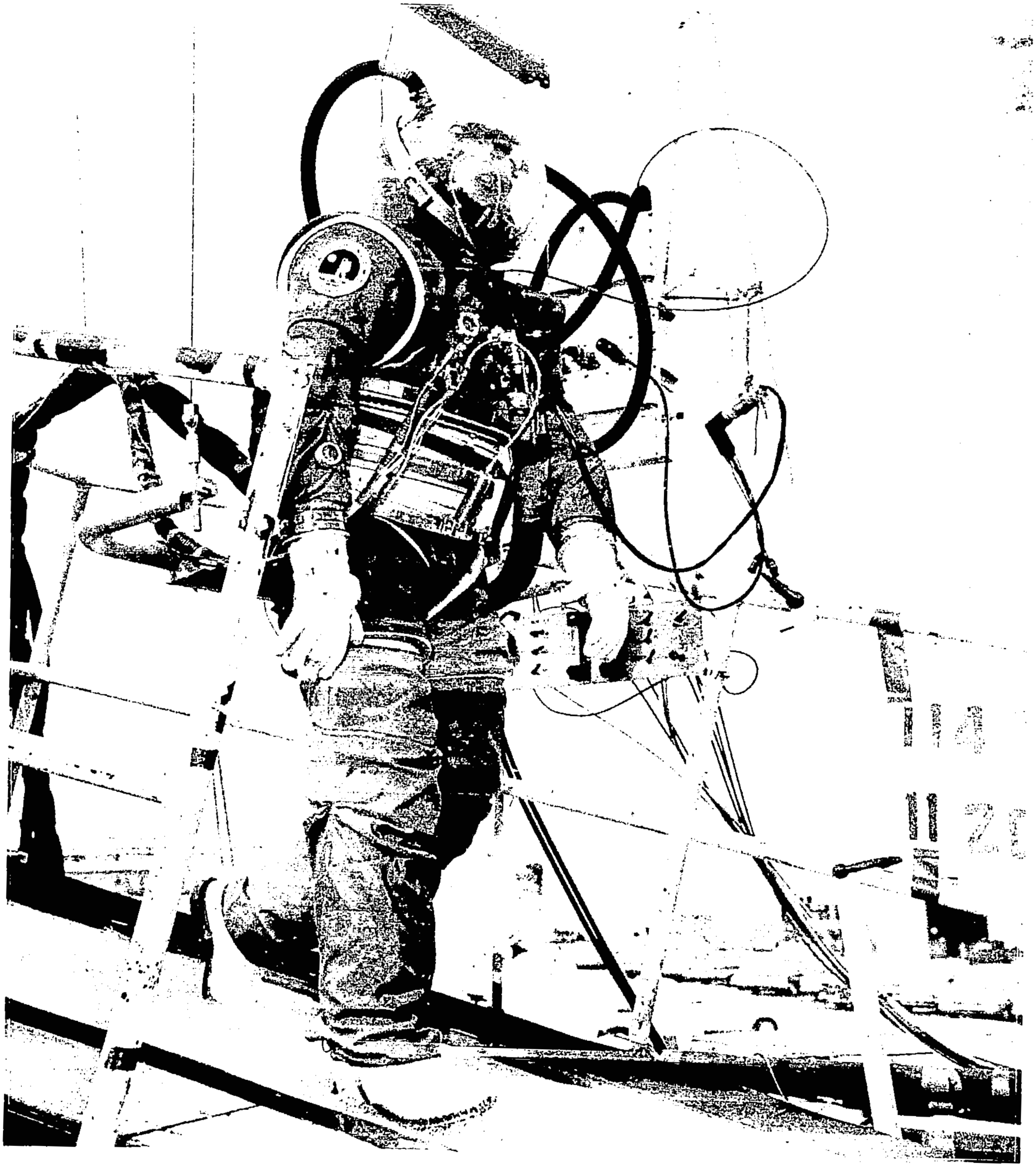


Fig. 2-33. Metabolic analyzer package mounted on bungee cords near the subject's left shoulder

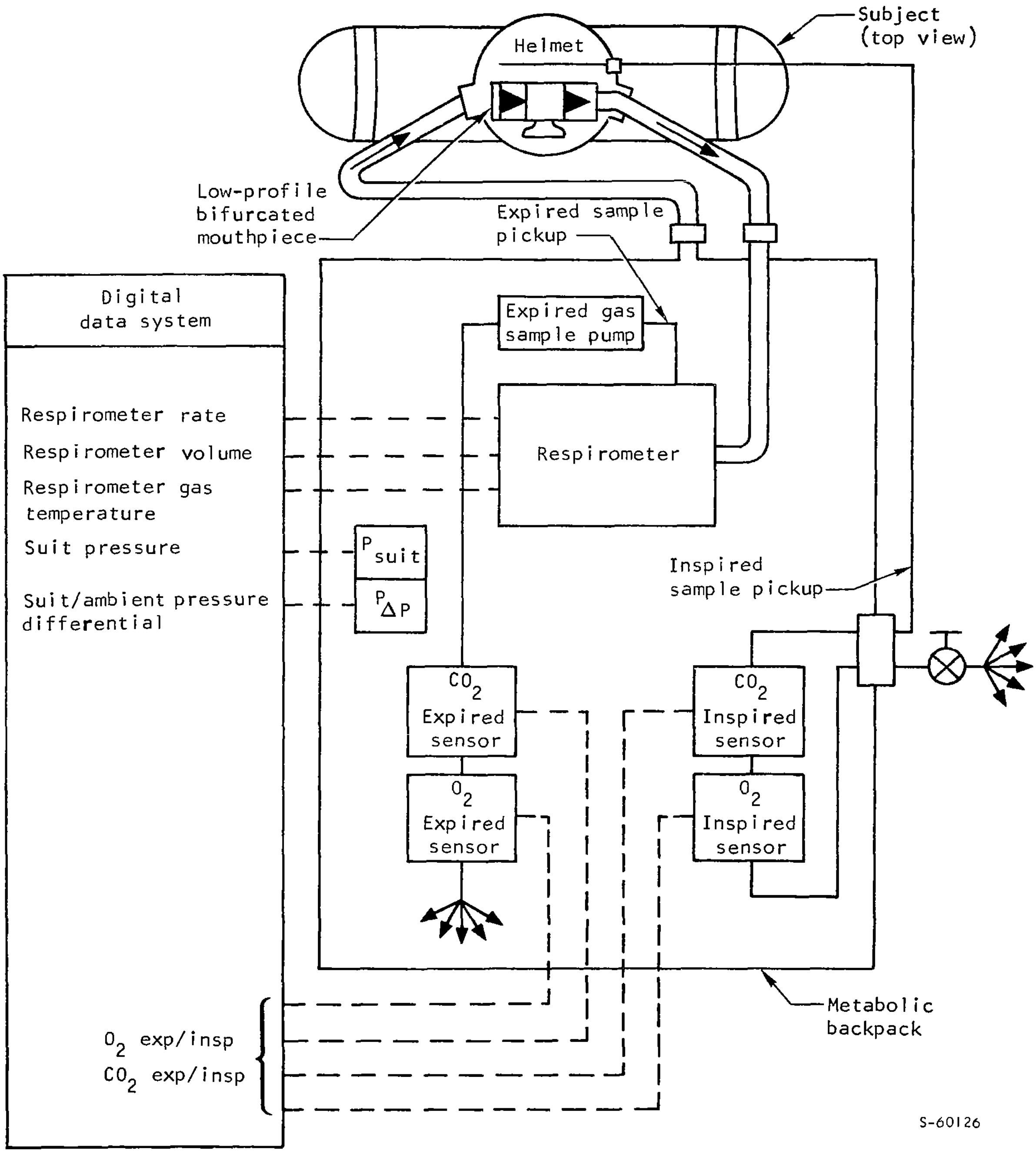


Fig. 2-34. Metabolic rate analyzer system schematic

The data from the respirometer and from the O_2 and CO_2 sensors, the temperature of the gases, and the total pressure in the backpack provide all the information needed to calculate oxygen consumption, carbon dioxide production, and the respiratory exchange ratio.

The external configuration of the metabolic backpack is shown in fig. 2-32. The connections for the breathing hoses are shown on the upper right corner of the pack. The various electrical connectors are seen on the front of the pack. The connectors on the center of the left panel are for input of calibration gases while the knob in the lower left is a zero adjustment knob for one of the LB-I CO_2 analyzers found in the pack. A similar adjustment control for the second LB-I analyzer is located on the opposite panel.

The internal configuration of the metabolic analyzer pack is shown in fig. 2-35. The Franz-Mueller modified for electronic readout is located in the upper portion of the pack. The respired gas is ducted into the respirometer through the tube on the right. The gas is exhausted from the respirometer into the general volume and returned to the suit helmet. As the respired volume is measured, the respirometer extracts an average sample of the expired gas and pumps it through the LB-I CO_2 analyzer located on the center right.

The inspired air sample is taken from the inlet side of the bifurcated mouthpiece located in the helmet. Fig. 2-36 shows the helmet and one-way valve assembly. The sample is drawn through a line connected between the side of the helmet and the backpack. The inspired sample passes to the LB-I analyzer on the lower right and then to a second polarographic oxygen sensor. The sample is then vented outside of the backpack to the atmosphere. The two oxygen sensors are located in a single machined block located on the right center of the backpack. Directly under the oxygen sensors are two pressure transducers for backpack pressure and backpack-to-ambient pressure differential. The respired volume temperature is measured by a thermistor located below the 90^0 elbow connected to the inlet of the respirometer.

Calibration Procedures

The components of the metabolic backpack were calibrated before and after each group of tests performed on a subject. Calibration of the gas analyzers were the most critical of the measurements made and these instruments were the most susceptible to calibration changes over time. The power to the gas analyzers was never turned off throughout the test period except for repairs. This procedure minimized the calibration drift during the tests.

The gas analyzers were calibrated by passing gases of known oxygen and carbon dioxide concentrations through the gas analyzers at the same test pressures at which the subject would be pressurized. At least a 4-point calibration curve was generated for each gas analyzer. The gas analyzer calibration schematic is shown in fig 2-37.

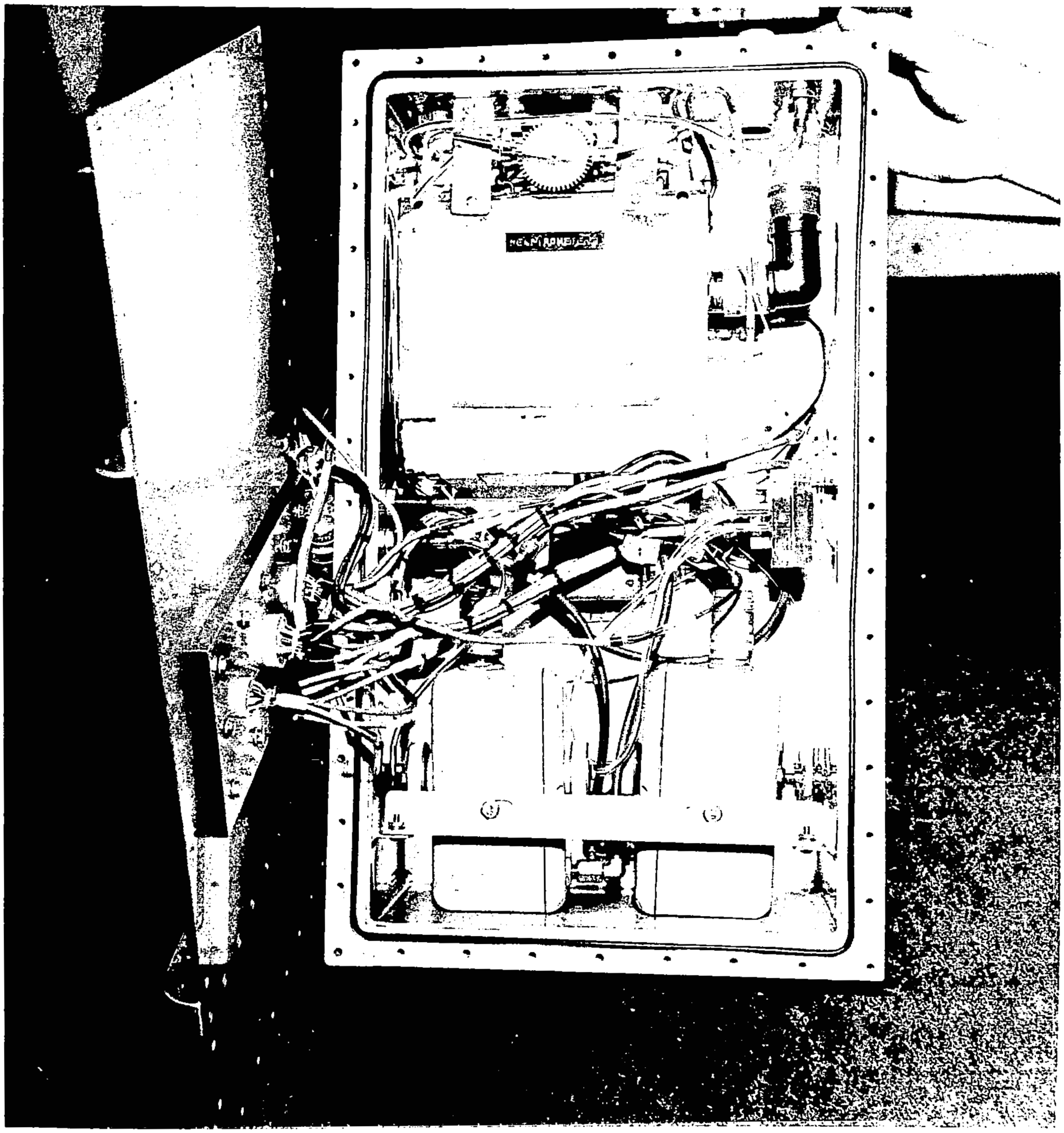


Fig. 2-35. Internal configuration of the metabolic analyzer package

Fig. 2-36. Breathing valve assembly mounted in helmet

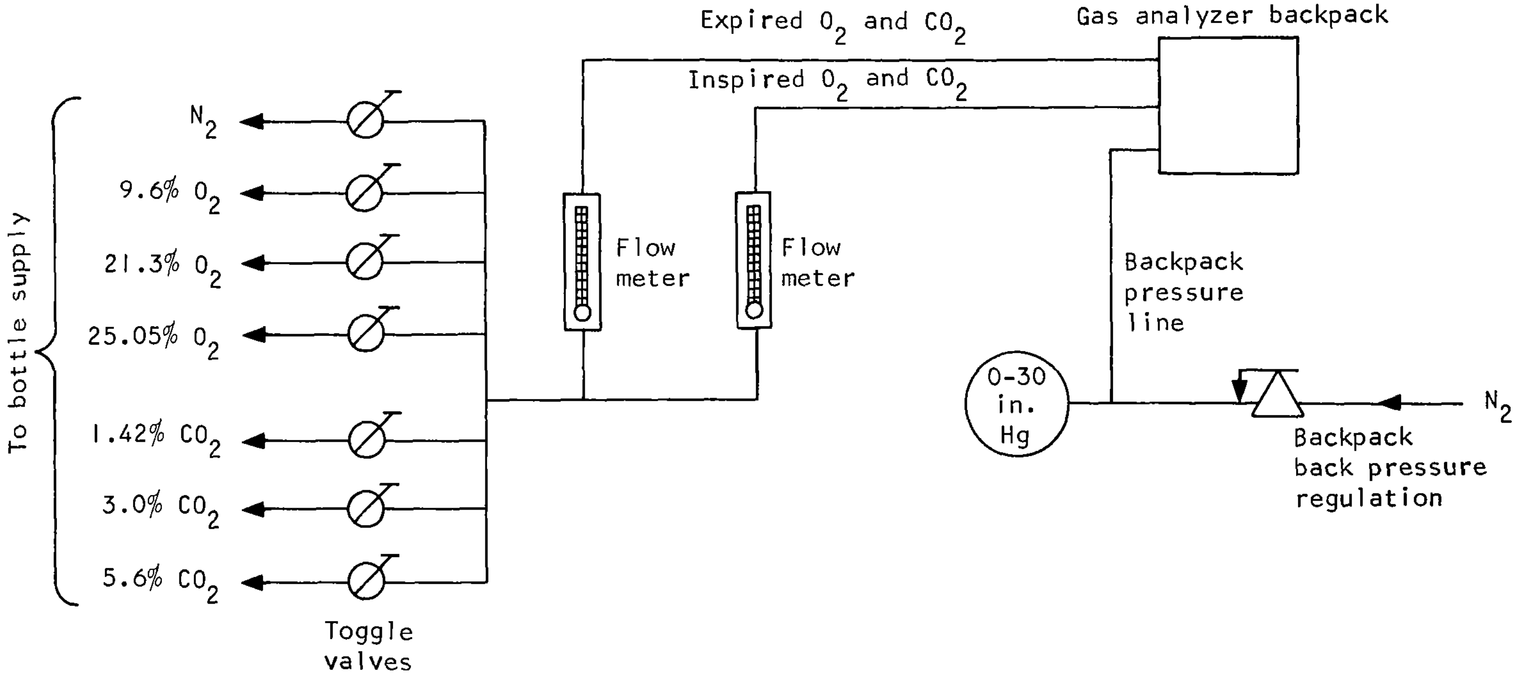


Fig. 2-37. Gas calibration schematic

Time Constant for Gas Analysis

The time required for the gases sampled at the suit helmet to reach the analyzers (line washout time) and the time constants for the sensing mechanisms are tabulated in table 2-5 and presented graphically in fig. 2-38.

TABLE 2-5.-- TIME CONSTANT TABULATION

Gas	Gas sample (X) change, percent	Sensor time constant, sec	Line washout time, sec
O_2 (Inspired)	0 to 9.6	4.0	18
O_2 (Inspired)	0 to 9.6	4.4	18
O_2 (Expired)	0 to 9.6	6.4	18
O_2 (Expired)	0 to 9.6	5.4	18
O_2 (Inspired)	9.6 to 21.3	5.4	18
O_2 (Inspired)	9.6 to 21.3	4.8	18
O_2 (Expired)	9.6 to 21.3	8.0	18
O_2 (Expired)	9.6 to 21.3	6.7	18
CO_2 (Inspired)	3.0 to 0.0	1.3	18
CO_2 (Expired)	3.0 to 0.0	1.7	18
CO_2 (Inspired)	1.42 to 3.0	1.7	18
CO_2 (Expired)	1.42 to 3.0	1.3	18
CO_2 (Inspired)	3.0 to 5.6	1.9	18
CO_2 (Expired)	3.0 to 5.6	1.8	18

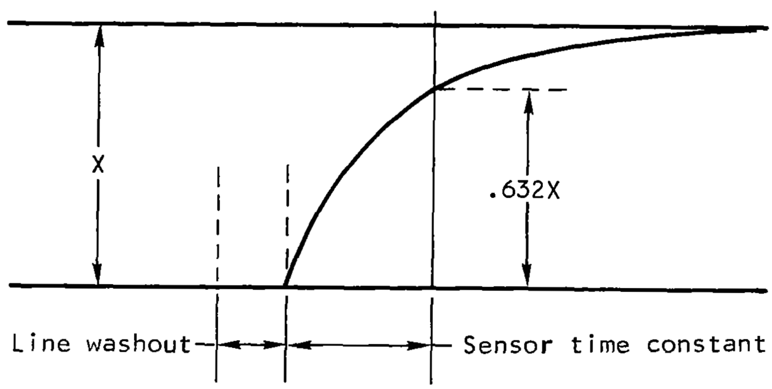


Fig. 2-38. Diagram of time constant

SECTION 3.- PROCEDURES AND TEST DESIGN

SUBJECT SELECTION

Two subjects were used in this study. Both had previous pressure suit training and served as subjects with the Gemini G2C, Apollo A7L, and EX-1A pressure suits. They were selected because of the excellence of their attitude, health, and physical capabilities. Because of prior experience, the subjects were familiar with the EX-1A pressure suit, with locomotion on treadmills using various 1/6-g simulators, and with the test procedure. Table 3-1 shows the anthropometric characteristics of these two subjects.

TABLE 3-1.-- ANTHROPOMETRIC CHARACTERISTICS OF TEST SUBJECTS

Subject	Age, yr	Height		Weight		Body surface area, m^2
		in.	cm	lb	kg	
R. W.	33	70.5	179.1	168.0	76.2	1.94
R. B.	31	70.0	177.8	162.0	73.5	1.90

EXPERIMENTAL DESIGN

The experimental program was to test the effects of the following independent variables: surface grades, lunar surface conditions, backpack weights, pull cart weights, velocity, and locomotive gait metabolic cost. Tests were conducted using a blow-by piston lunar gravity simulator suspension system and the EX-1A space suit. The experimental design of the tests is shown in table 1-1, section 1.

TEST PROCEDURE

Subject Preparation

The subjects arrived at the dressing room of the test facility in a post absorptive state. The subjects completed filling out their subject questionnaires and were interviewed to determine if they had any symptoms that would indicate an ailment that might affect their ability, the tests, or the data.

They stripped to the nude, weighed, and donned the lower undergarments worn with the pressure suit. The bioinstrumentation was then put in place and EKG signal output checked. The subject completed donning the upper half of the undergarments and any necessary padding required. The subject weighed himself again and filled out a data tag indicating his weight and rectal probe serial number. The suit was carted out to the test site where it was donned.

Blow-by Piston Suspension Procedure

Prior to subject arrival at the test site the trolley and beam air pads were activated and checked for proper operation. Servicing and calibration of equipment and instrumentation were accomplished. When the subject arrived he donned the bottom half of the EX-1A suit. The EX-1A pickup ring support was left attached to the bottom half of the suit. The subject backed into the lower half of the whiffle tree suspension, and the pickup ring was bolted into place. Each subject's center of gravity was predetermined earlier and marked to assist in center of gravity location. The blow-by suspension system was activated, and a 50-lb force was set to tension the suspension cables and whiffle tree suspension. The upper half of the suit was then donned. Internal ventilation hoses and bioinstrumentation plug connections were made, and the suit closure ring was locked into place. External ventilation hoses were connected to the suit; the external bioinstrumentation plug was connected to the suit. Ventilation flow was initiated through the suit. The subject's gloves were locked into place and his nose clip taped on. The bioinstrumentation and communication signals were checked before locking the helmet into place. Metabolic backpack hose connections to the helmet were attached and clamped in place. The inspired gas sample line from the helmet was also connected. All suit connections or closures were then double checked prior to pressurizing the suit to 3.7 psig. The blow-by piston suspension tension was increased to balance the subject off the treadmill to check the pitch and roll axis center-of-gravity locations. Adjustments were made to allow the subject an equal ability of motion in either direction of rotation about the pitch or roll axis. The subject was then held down onto the treadmill surface and the turbine air supply set at 10 psig with no flow through the pressure regulator valve. The bypass flow through the pressure regulator was then increased until the correct tension was reached. Cable tension was calculated for a simulated 1/6-g field from the subject's suited weight including the backpack weight.

Data Collection

After completion of the pretest procedures, the tests were started. The first test point for every test condition was the resting metabolic rate measurement. This was measured at time zero and +2 min. After recording the +2-min data point, the treadmill was started and the subject performed the scheduled task for a period of 15 min. Recording of all physiological parameters was made during the last 5 min of the test at 1-min intervals. The subject rested until all physiological parameters returned to normal rest levels (e.g., heart rate, temperature). The second test could then commence. There was an absolute minimum period of 8 min (6 min at the end of one test, plus 2 min at the start of the next test) between periods of exercise on the treadmill. The average resting duration, however, was approximately 20 min. The sequence of test events was random among subjects to reduce the probability of other effects in the data.

DATA REDUCTION

Raw data were collected during this experiment at intervals of 1 min, and sufficient personnel and recording equipment were employed to record all the data within the same 15-sec period. The data were recorded directly from the instruments on data sheets, punched tape, and strip-chart recorders. The data was subsequently entered, along with a preprogram, in an SDS 940 computer used on a time sharing basis. At all points of testing, the consistency of time, test conditions, subject designation, and data were compared for accuracy. The results obtained and presented in this report have been cross checked with all pertinent control points to ensure proper comparative data. The computer output provided all data required for interpretation of subsequent analysis, whether or not these data were required for the computations.

The various equating analytical computations and subsequent statistical analyses were performed as described in NASA CR-1402 (ref. 1).

SECTION 4.-RESULTS AND DISCUSSION

This section presents the test results and the effects of the independent variables (listed in table 1-1, Section 1) on the dependent variables. Since the tests performed were exploratory in nature and only two subjects were used per test condition, statistical analyses were not performed on the data. The small sample size (only two subjects) reduces the validity of the absolute value of mean as representing the full estimate of the mean of a population performing the same tasks. However, the data obtained do estimate the general cost of performing each specific task. The comparisons drawn between these data and other data will always be couched to reflect the exploratory nature of this test series.

The data will be presented in the order shown in table 1-1, Section 1. The dependent variables for which data are reported include metabolic rate, carbon dioxide production, oxygen consumption, respiratory rate, expired minute ventilation, rectal temperature, and step rate.

INTERNAL PRESSURE SUIT CONDITIONS

The ranges of observed values for both monitored and controlled suit conditions are shown in table 4-1. The suit gas flow, pressure, and inlet temperature were controlled parameters. Suit inlet gas temperature and pressure were maintained within narrow limits. Suit outlet temperatures reached similar levels regardless of exercise (as reported previously, refs. 1 and 3). Inlet dewpoint was always $0^{\circ}F$.

All tests were performed outdoors over a 50-day period. The ambient temperature during the test period ranged from 58° to $79^{\circ}F$. The barometric pressure ranged from 29.74 to 30.13 in. Hg.

TABLE 4-I.-- SUMMARY OF THE RANGE OF VALUES FOR EX-IA INTERNAL SUIT CONDITIONS FOR ALL EXPERIMENTAL MODES

Test	Ventilated mode	Gas flow, cfm	Suit pressure, psig	Temperature, °F		Dewpoint, °F	
				Inlet	Outlet	Inlet	Outlet
Self-locomotion on a coarse lunar soil simulant	Pressurized	14.0 to 22.0	3.65 to 3.80	50 ±3	65 to 80	0	16 to 33
Self-locomotion on Apollo 11 soil simulant Cart pulling on Apollo 11 soil simulant	Pressurized	10.0 to 22.0	3.65 to 3.75	50 ±3	64 to 76	0	16 to 31

SELF-LOCOMOTION ON A COARSE LUNAR SOIL SIMULANT

Metabolic Rate

The treatment and handling of metabolic rate data obtained during pressure suited locomotion testing have been described extensively in NASA Report CR-1402 (ref. 1). The steady-state metabolic costs for self-locomotion on a coarse lunar soil simulant for each of the subjects are presented in table 4-2. The sample means ± one standard deviation for each test mode are given in table 4-3. The values presented in table 4-3 are shown graphically in figs. 4-1 through 4-4.

As was expected, metabolic rates are increased by velocity. Metabolic rates are generally increased by load carrying and when ascending slopes. The metabolic cost of ascending a 15^0 slope was excessive and neither subject was able to traverse such a slope at 4 km/hr. The heart rates of both subjects reached 180 beats/min within 8 min of exercise and were not able to keep their position on the treadmill and the tests were terminated. Energy requirements are lower for descending slopes than for walking on a level surface, regardless of loads carried. There are no indications within these data that there are any differences between running and loping at the same velocities. Additional data are required to ascertain any differences between loping and running gaits. All other effects noted above are consistent with the findings noted with the G-2C pressure suit in ref. 1.

Carbon Dioxide Production, Oxygen Consumption, and Minute Ventilation

The data obtained for each of these dependent variables are presented in tabular form. There are two tables for each dependent variable. The individual observations are given in the first table and the means and standard deviations for each test mode are presented in the second table. Tables 4-4 and 4-5 show the observations for carbon dioxide production, tables 4-6 and 4-7 show oxygen consumptions, and tables 4-8 and 4-9 show expired minute ventilations. The statistical inferences noted earlier for differences in metabolic rates between test modes are equally pertinent to these variables.

Respiratory Rates

The respiratory rate data are given in tables 4-10 and 4-11. An evaluation of table 4-11 would indicate that, in general, respiratory rates are increased for test modes having high energy requirements. However, if the -15^0 slope data are considered, it is apparent that respiratory rate is not a simple function of metabolic rate but that there are other inputs such as emotional state and stress. No specific conclusions can be made as to the physiological response of these two subjects based on respiration rate. Respiratory rate is normally considered a poor indicator of physiologic response to a given situation.

Rectal Temperature

Rectal temperatures are presented in tables 4-12 and 4-13. These data show that there was no difference in rectal temperature between test modes, regardless of the energy requirements. In fact the greatest change during a particular test was 0.2°F increase during the 4 km/hr walk on a +15° slope while carrying a simulated 240-lb pack, and that test was terminated for physiological reasons. These data demonstrate that there was no heat storage during any test so that there was no temperature effect on the rate of chemical reaction and oxygen consumptions were not affected.

Step Rate

Step rate data are given in tables 4-14 and 4-15. Data on walking on simulated lunar soils in simulated lunar gravity are very sparse. However, there appears to be little difference between these data and those reported for testing with the G-2C and reported in ref. 1.

TABLE 4-2.-- INDIVIDUAL VALUES OF METABOLIC COST

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Metabolic cost, kcal/min, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	3.38 4.60	5.10 4.71				
RW RB	0	75	Run			5.47 6.23	8.52 8.66		
RW RB	0	75	Lope					7.49 7.07	9.22 7.19
RW RB	0	240	Walk	3.95 3.09	8.87 6.92				
RW RB	0	240	Run			10.41 7.56	13.90 11.80		
RW RB	0	240	Lope					11.70 8.21	12.31 8.84
RW RB	+15	75	Walk	5.78 4.99	7.67 8.71				
RW RB	+15	240	Walk	7.32 11.56	(a) (a)				
RW RB	-15	75	Walk	2.44 2.31	3.66 4.11				
RW RB	-15	240	Walk	2.95 2.23	4.56 4.42				

[a]Subjects could not perform at these conditions

TABLE 4-3.-- AVERAGE METABOLIC COST

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-IA pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Metabolic cost, kcal/min, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	3.99 ±0.86[a]	4.91 ±0.28				
0	75	Run			5.85 ±0.54	8.59 ±0.10		
0	75	Lope					7.28 ±0.39	8.21 ±1.44
0	240	Walk	3.52 ±0.61	7.90 ±1.38				
0	240	Run			8.99 ±2.02	12.85 ±1.48		
0	240	Lope					9.95 ±2.47	10.58 ±2.45
+15	75	Walk	5.38 ±0.56	8.19 ±0.74				
+15	240	Walk	9.44 ±3.0	--				
-15	75	Walk	2.38 ±0.32	3.89 ±0.32				
-15	240	Walk	2.59 ±0.51	4.49 ±0.10				

[a]Mean ±1 standard deviation

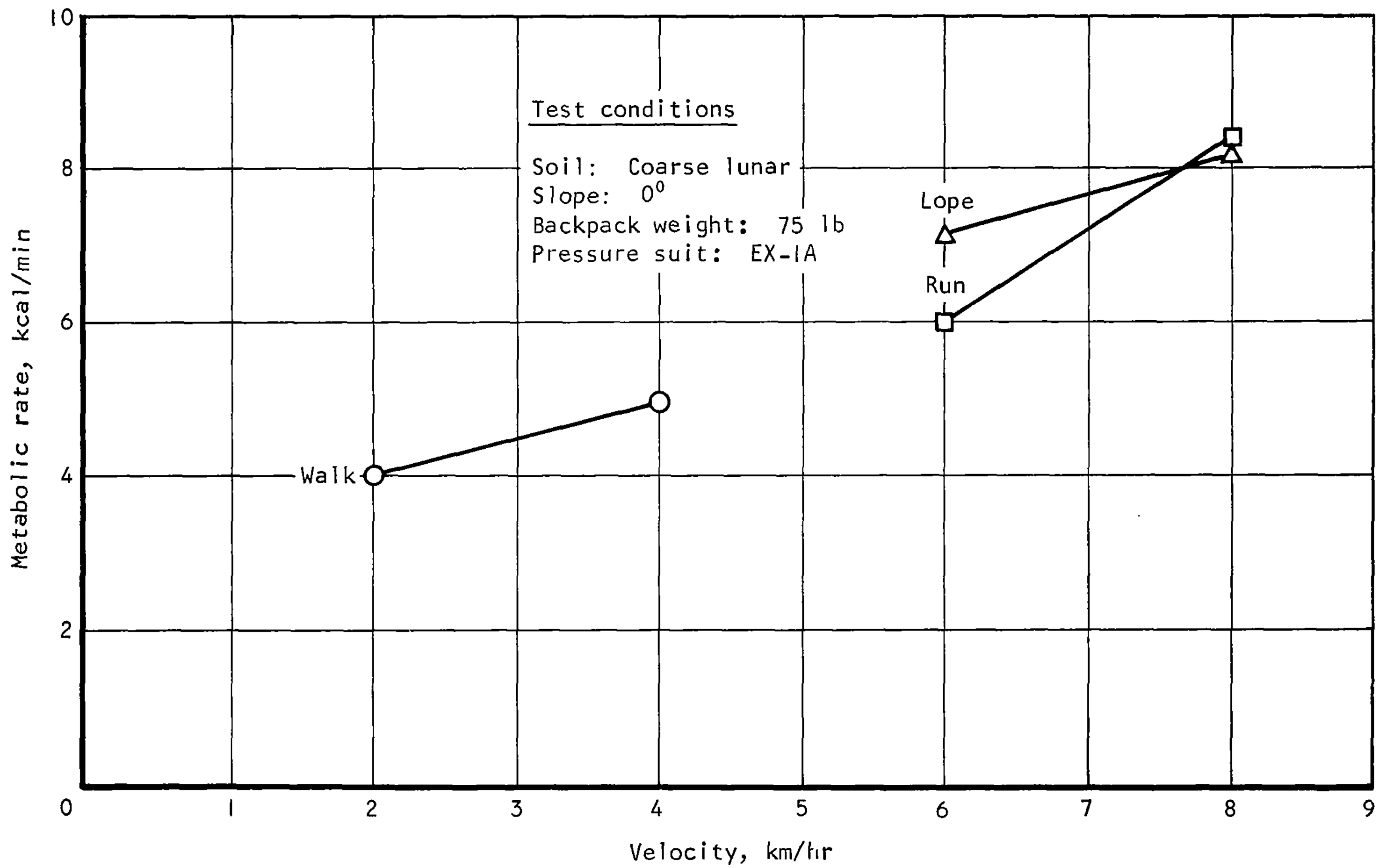


Fig. 4-1. Metabolic rate versus velocity for various gaits (75-lb backpack)

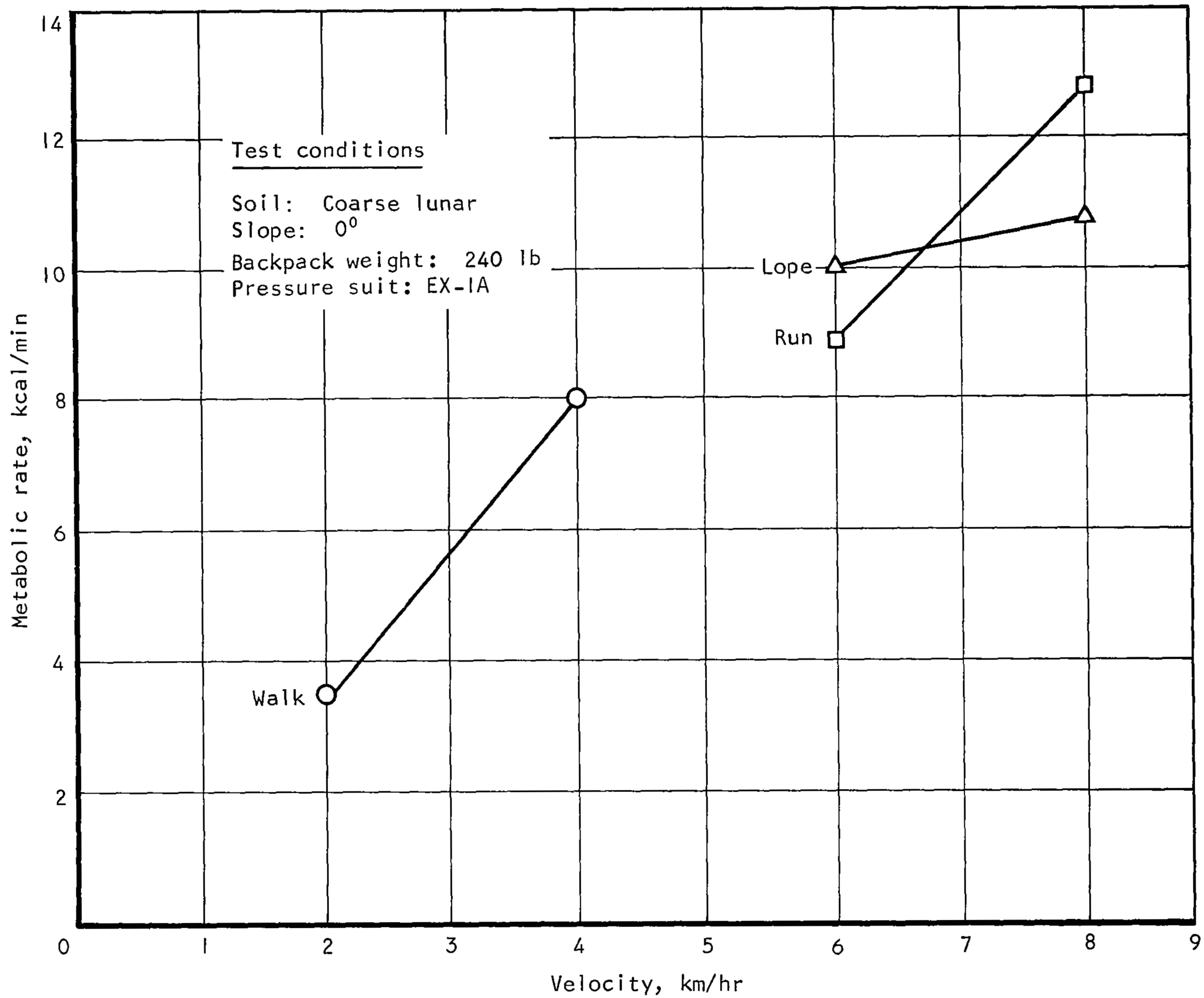


Fig. 4-2. Metabolic rate versus velocity for various gaits (240-lb backpack)

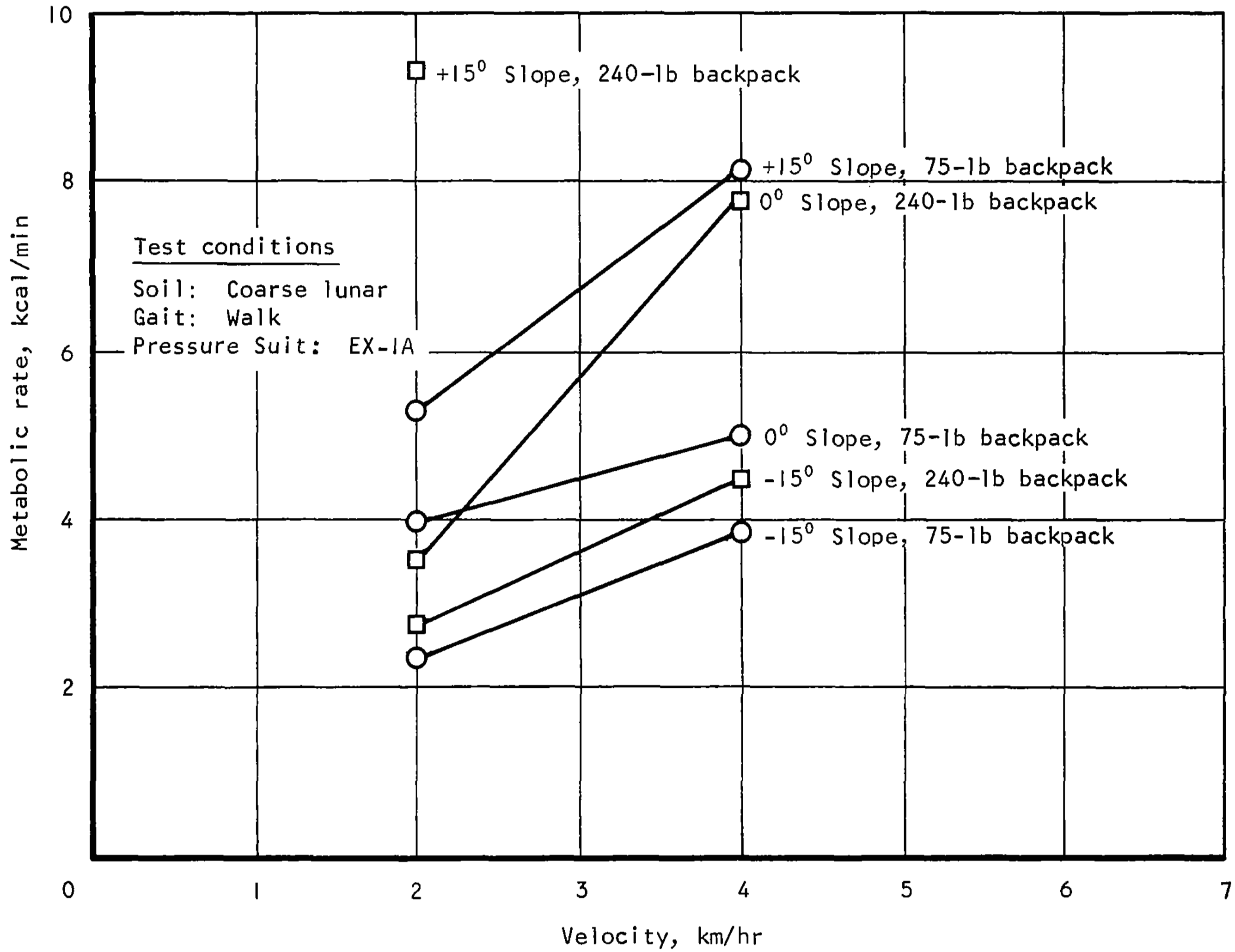


Fig. 4-3. Metabolic rate versus velocity for various slopes and backpack weights

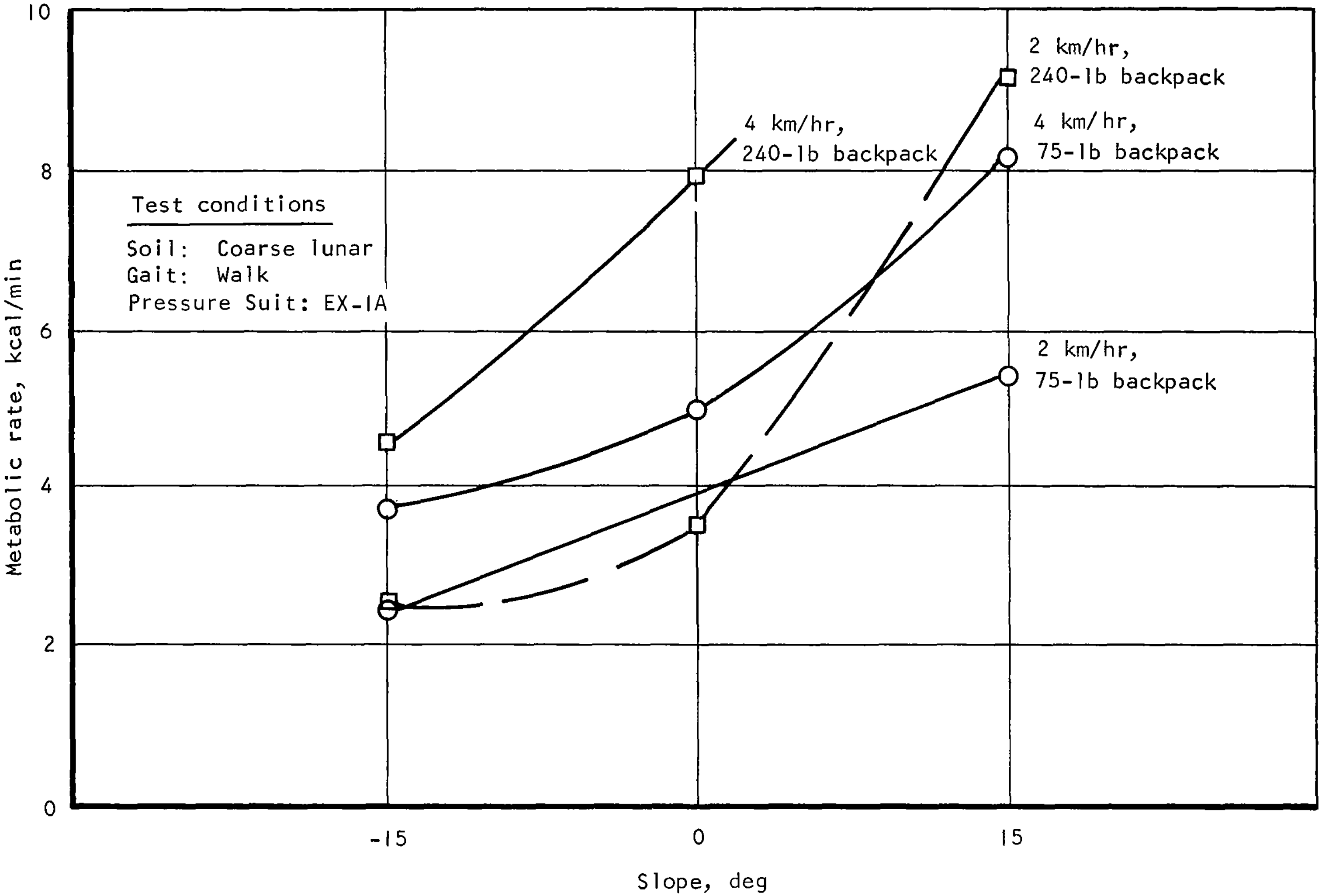


Fig. 4-4. Metabolic rate versus slope for various velocities and backpack weights

TABLE 4-4.-- INDIVIDUAL VALUES OF CARBON DIOXIDE PRODUCTION

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Carbon dioxide production, liters/min-STPD, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	0.575 0.527	0.967 0.852				
RW RB	0	75	Run			1.080 1.052	1.394 1.253		
RW RB	0	75	Lope					1.153 1.135	1.339 1.319
RW RB	0	240	Walk	0.649 0.705	1.336 1.369				
RW RB	0	240	Run			1.338 2.276	1.441 1.636		
RW RB	0	240	Lope					2.47 1.520	1.454 1.436
RW RB	+15	75	Walk	1.391 0.895	3.007 0.456				
RW RB	+15	240	Walk	2.022 1.298	(a) (a)				
RW RB	-15	75	Walk	0.400 0.377	0.798 0.709				
RW RB	-15	240	Walk	0.420 0.377	0.709 0.798				

[a]Subjects could not perform at these conditions

TABLE 4-5.-- AVERAGE CARBON DIOXIDE PRODUCTION

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-IA pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Carbon dioxide production, liters/min-STPD, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	0.557 ±0.034[a]	0.910 ±0.081				
0	75	Run			1.066 ±0.020	1.324 ±0.100		
0	75	Lope					1.144 ±0.013	1.329 ±0.014
0	240	Walk	0.677 ±0.040	1.353 ±0.023				
0	240	Run			1.807 ±0.663	1.539 ±0.138		
0	240	Lope					1.995 ±0.672	1.445 ±0.013
+15	75	Walk	1.143 ±0.534	1.732 1.804				
+15	240	Walk	1.660 ±0.512	--				
-15	75	Walk	0.389 ±0.016	0.754 ±0.063				
-15	240	Walk	0.399 ±0.030	0.754 ±0.63				

[a]Mean ±1 standard duration

TABLE 4-6.-- INDIVIDUAL VALUES OF OXYGEN CONSUMPTION

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Oxygen consumption, liters/min-STPD, at--					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	0.699 0.761	1.005 1.106				
RW RB	0	75	Run			1.086 1.185	1.183 1.639		
RW RB	0	75	Lope					1.614 1.513	1.397 1.456
RW RB	0	240	Walk	0.826 0.642	1.107 1.416				
RW RB	0	240	Run			1.366 2.153	1.771 1.480		
RW RB	0	240	Lope					3.107 1.721	2.515 1.676
RW RB	+15	75	Walk	1.685 0.968	3.661 0.556				
RW RB	+15	240	Walk	2.440 1.699	(a) (a)				
RW RB	-15	75	Walk	0.483 0.457	0.985 0.858				
RW RB	-15	240	Walk	0.456 0.611	0.858 0.965				

[a]Subjects could not perform at these conditions.

TABLE 4-7.-- AVERAGE OXYGEN CONSUMPTION

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-IA pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Oxygen consumption, liters/min-STPD, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	0.730 ±0.044[a]	1.056 ±0.072				
0	75	Run			1.136 ±0.070	1.411 ±0.322		
0	75	Lope					1.569 ±0.071	1.699 ±0.426
0	240	Walk	0.734 ±0.130	1.262 ±0.218				
0	240	Run			1.760 ±0.556	1.623 ±0.206		
0	240	Lope					2.414 ±0.980	2.096 ±0.593
±15	75	Walk	1.327 ±0.507	2.109 ±2.196				
+15	240	Walk	2.070 ±0.524	--				
-15	75	Walk	0.470 ±0.018	0.912 ±0.076				
-15	240	Walk	0.534 ±0.109	0.912 ±0.076				

[a]Mean ±1 standard duration

TABLE 4-8.-- INDIVIDUAL VALUES OF MINUTE VENTILATION

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-IA pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Minute ventilation, liters/min-BTPS, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	18.345 16.028	27.162 27.359				
RW RB	0	75	Run			29.740 28.996	36.995 39.636		
RW RB	0	75	Lope					48.730 36.295	63.350 42.500
RW RB	0	240	Walk	21.250 20.820	37.200 41.076				
RW RB	0	240	Run			47.009 56.964	58.012 58.417		
RW RB	0	240	Lope					64.611 50.595	53.302 56.964
RW RB	+15	75	Walk	42.385 24.707	78.498 15.502				
RW RB	+15	240	Walk	54.982 36.656	(a) (a)				
RW RB	-15	75	Walk	11.358 10.427	20.700 18.424				
RW RB	-15	240	Walk	10.427 15.118	18.427 20.700				

[a]Subjects could not perform at these conditions.

TABLE 4-9.-- AVERAGE MINUTE VENTILATION

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-IA pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Minute ventilation, liters/min-BTPS, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	17.187 ±1.638[a]	22.261 ±6.932				
0	75	Run			29.368 ±0.526	38.316 ±1.867		
0	75	Lope					42.513 ±8.793	52.925 ±14.743
0	240	Walk	21.035 ±0.304	39.138 ±2.741				
0	240	Run			57.987 ±7.039	58.215 ±0.286		
0	240	Lope					57.603 ±9.911	55.133 ±2.589
+15	75	Walk	33.546 ±12.500	47.00 ±44.545				
+15	240	Walk	45.819 ±12.958	--				
-15	75	Walk	10.893 ±0.658	19.562 ±1.609				
-15	240	Walk	12.773 ±3.317	19.564 ±1.607				

[a]Mean ±1 standard duration

TABLE 4-10.-- INDIVIDUAL VALUES OF RESPIRATORY RATE

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Respiratory rate, breaths/min, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	18.7 19.6	20.5 21.9				
RW RB	0	75	Run			17.3 21.2	20.1 24.7		
RW RB	0	75	Lope					24.6 26.3	34.6 26.9
RW RB	0	240	Walk	17.7 19.7	24.6 24.4				
RW RB	0	240	Run			23.4 27.0	28.1 29.6		
RW RB	0	240	Lope					30.2 26.2	28.9 27.0
RW RB	+15	75	Walk	26.3 20.0	31.2 18.2				
RW RB	+15	240	Walk	29.2 22.5	(a) (a)				
RW RB	-15	75	Walk	21.7 26.4	20.5 24.5				
RW RB	-15	240	Walk	26.4 21.2	23.0 24.5				

[a]Subjects could not perform at these conditions.

TABLE 4-11.-- AVERAGE RESPIRATORY RATE

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Respiratory rate, breaths/min, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	19.2 ±0.6[a]	21.2 ±1.0				
0	75	Run			29.3 ±2.8	224 ±3.3		
0	75	Lope					25.5 ±1.2	30.8 ±5.4
0	240	Walk	18.7 ±1.4	24.5 ±0.1				
0	240	Run			25.2 ±2.5	28.9 ±1.1		
0	240	Lope					28.2 ±2.8	28.0 ±1.3
+15	75	Walk	23.2 ±4.5	24.7 ±9.2				
+15	240	Walk	25.9 ±4.7	--				
-15	75	Walk	24.1 ±3.3	22.5 ±2.8				
-15	240	Walk	23.8 ±3.7	23.8 ±1.1				

[a]Mean ±1 standard duration

TABLE 4-12.-- INDIVIDUAL VALUES OF RECTAL TEMPERATURE

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Rectal temperature, °F, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	98.1 99.4	98.0 99.9				
RW RB	0	75	Run			99.3 99.4	99.8 99.8		
RW RB	0	75	Lope					100.6 99.9	100.1 99.4
RW RB	0	240	Walk	99.5 100.1	99.4 99.1				
RW RB	0	240	Run			99.6 99.3	99.3 99.8		
RW RB	0	240	Lope					100.2 100.5	100.4 100.3
RW RB	+15	75	Walk	99.2 99.3	99.4 99.6				
RW RB	+15	240	Walk	99.8 99.8	(a) (a)				
RW RB	-15	75	Walk	99.3 99.6	99.4 99.5				
RW RB	-15	240	Walk	99.6 98.6	99.4 99.5				

[a]Subjects could not perform at these conditions.

TABLE 4-13.-- AVERAGE RECTAL TEMPERATURE

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Rectal temperature, °F, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	98.8 ±0.9[a]	99.0 ±1.3				
0	75	Run			99.4 ±0.1	99.8 ±0		
0	75	Lope					100.3 ±0.5	99.8 ±0.5
0	240	Walk	99.8 ±0.4	99.3 ±0.2				
0	240	Run			99.5 ±0.2	99.6 ±0.4		
0	240	Lope					100.4 ±0.2	100.4 ±0.1
+15	75	Walk	99.3 ±0.1	99.5 ±0.1				
+15	240	Walk	99.8 ±0	--				
-15	75	Walk	99.5 ±0.2	99.5 ±0.1				
-15	240	Walk	99.1 ±0.7	99.5 ±0.1				

[a]Mean ±1 standard duration

TABLE 4-14.-- INDIVIDUAL VALUES OF STEP RATE

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Step rate, steps/min, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	71 78	105 108				
RW RB	0	75	Run			114 114	120 132		
RW RB	0	75	Lope					78 78	84 96
RW RB	0	240	Walk	72 78	96 114				
RW RB	0	240	Run			120 99.3	132 126		
RW RB	0	240	Lope					78 90	96 102
RW RB	+15	75	Walk	96 66	132 144				
RW RB	+15	240	Walk	114 66	(a) (a)				
RW RB	-15	75	Walk	66 60	66 90				
RW RB	-15	240	Walk	60 48	96 65				

[a]Subjects could not perform at these conditions.

TABLE 4-15.-- AVERAGE STEP RATE

[Self-locomotion; coarse lunar soil simulant; simulated lunar gravity; EX-IA pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Step rate, steps/min, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	74.5 ±4.9[a]	106.5 ±2.1				
0	75	Run			114 ±0	126 ±8.5		
0	75	Lope					78.0 ±0	90.0 ±8.5
0	240	Walk	75.0 ±4.2	105 ±12.7				
0	240	Run			109.7 ±14.6	129 ±4.2		
0	240	Lope					84.0 ±8.5	99.0 ±4.2
+15	75	Walk	81 ±21.2	138.0 ±8.5				
+15	240	Walk	90.0 ±33.9	--				
-15	75	Walk	63.0 ±4.2	73.0 ±17.0				
-15	240	Walk	54 ±8.5	80.5 ±21.9				

[a]Mean ±1 standard duration

SELF-LOCOMOTION ON AN APOLLO 11 SOIL SIMULANT

Metabolic Rates

Self-locomotion on the more cohesive lunar soil simulant patterned after soil data reported from the Apollo 11 flight resulted in steady-state metabolic costs presented in tables 4-16 and 4-17. A graphic display of the data are given in figs. 4-5, 4-6, and 4-7,

Examination of these data show the expected increase in energy requirements as velocity increases. It appears in fig. 4-5 that the energy cost of loping is higher than for running at the same velocities. However, the individual observations from table 4-16 show a disparity in cost between subjects for both loping at 6 km/hr and running at 6 and 8 km/hr. A reasonable estimate of the true relationship can only be derived by studying a larger population of subjects.

A comparison of the metabolic costs of carrying a 75-lb load on a level surface on either the coarse lunar soil simulant (fig. 4-1) or the more cohesive Apollo 11 soil simulant (fig. 4-5) do not reveal any recognizeable differences. This would indicate that the traction field is similar for both soil simulants insofar as locomotion at constant velocity in a straight line is concerned.

Differences between traversing slopes on the two soil simulants are unclear. However, it appears that there are no differences in energy expenditure at 2 km/hr for either ascending or descending a 15^0 slope. At 4 km/hr, it appears that the cost is higher for ascending a 15^0 slope and lower for descending a 15^0 slope on the Apollo 11 soil simulant than for the coarse lunar soil simulant.

Carbon Dioxide Production, Oxygen Consumption, and Minute Ventilation

The data for these dependent variables are presented in tables 4-18 through 4-23. The comparisons made for metabolic rates are applicable to the data obtained for carbon dioxide production, oxygen consumption, and expired minute ventilation.

Respiratory Rates and Rectal Temperature

Respiratory rates are shown in tables 4-24 and 4-25. Rectal temperatures are given in tables 4-26 and 4-27. It is apparent that the respiratory rates noted are relatively independent of exercise level. Changes in minute ventilation noted in table 4-23 are, therefore, occurring as a function of changes in total volume. Rectal temperatures were not different between test modes, and there were no changes during any specific test, indicating that there were no temperature effects on metabolic rates.

Step Rate

The stepping rate data for tests performed on the Apollo 11 soil simulant are given in tables 4-28 and 4-29. There are no readily apparent differences between these data and those obtained during locomotion on the coarse lunar soil simulant.

TABLE 4-16.-- INDIVIDUAL VALUES OF METABOLIC COST

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Metabolic cost, kcal/min, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	3.85 3.62	5.41 3.78				
RW RB	0	75	Run			7.62 4.51	7.46 6.89		
RW RB	0	75	Lope					10.41 6.87	10.62 6.03
RW RB	+15	75	Walk	6.45 4.85	11.32 9.68				
RW RB	-15	75	Walk	3.29 2.12	2.40 2.80				

TABLE 4-17.-- AVERAGE METABOLIC COST

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Metabolic cost, kcal/min, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	3.74 ±0.16[a]	4.60 ±1.15				
0	75	Run			6.06 ±2.20	7.18 ±0.40		
0	75	Lope					8.64 ±2.50	8.33 ±3.25
+15	75	Walk	5.65 ±1.13	10.50 ±1.16				
-15	75	Walk	2.71 ±0.83	2.60 ±0.28				

[a]Mean ±1 standard deviation

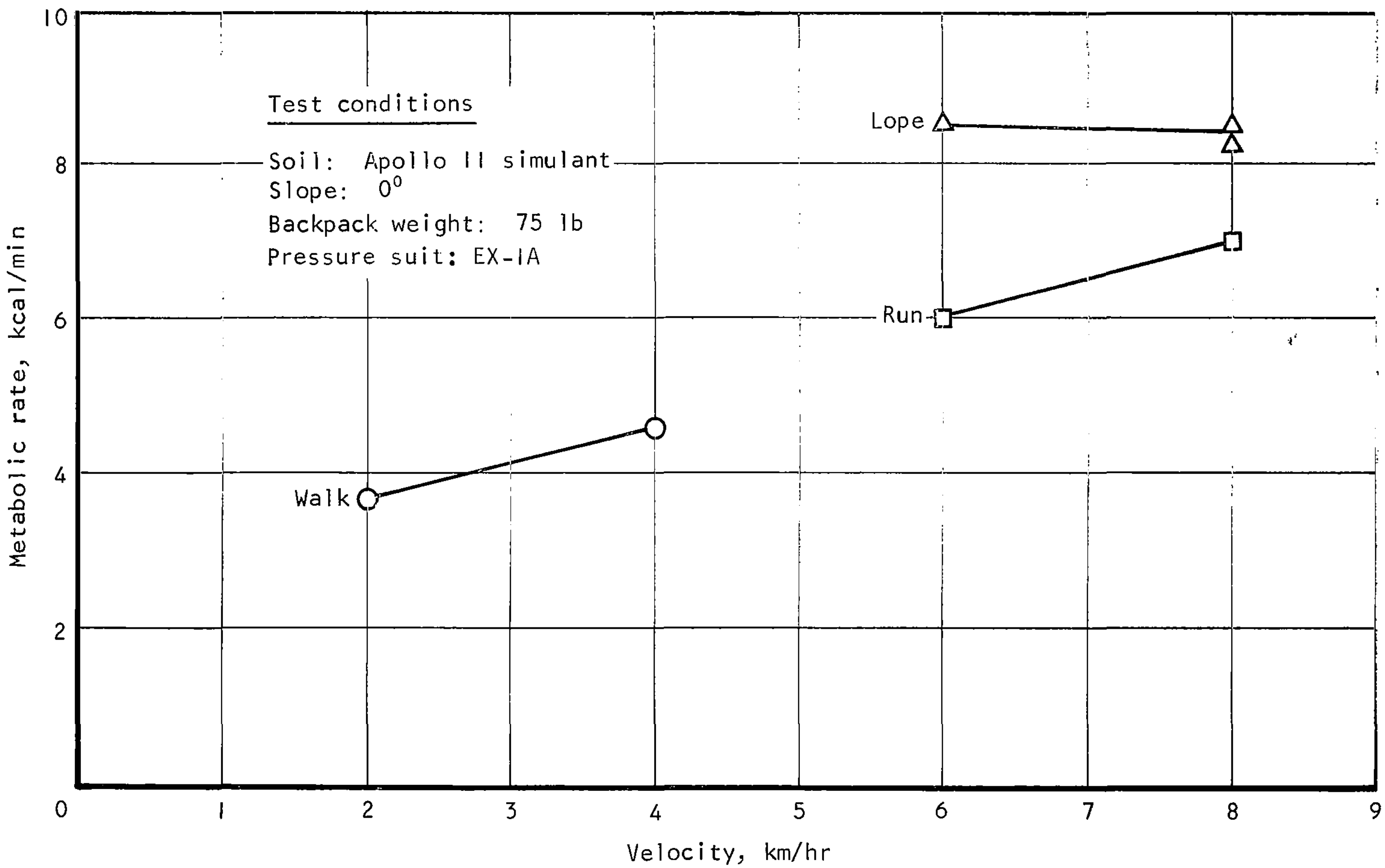


Fig. 4-5. Metabolic rate versus velocity for various gaits

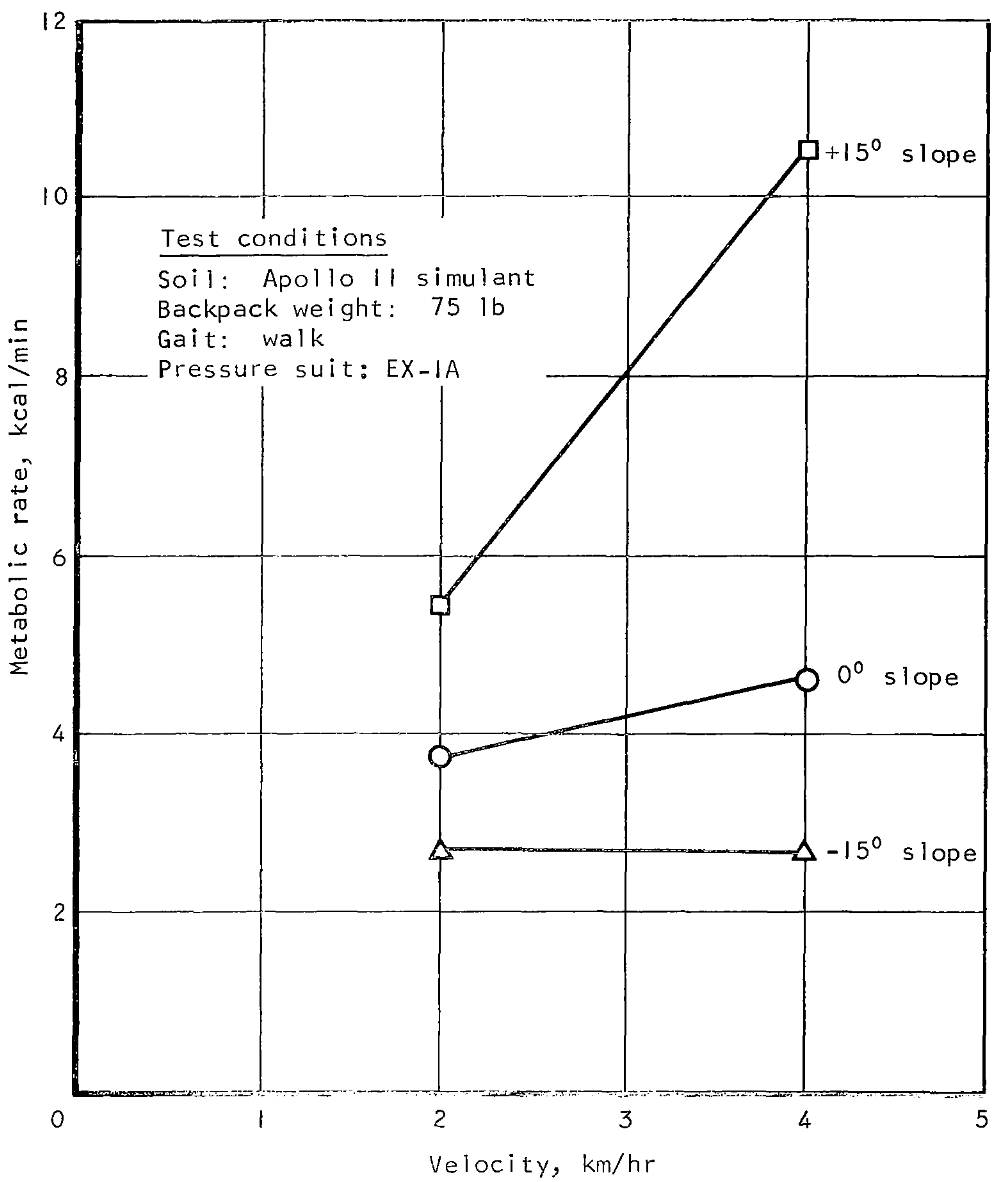


Fig. 4-6. Metabolic rate versus velocity for various slopes

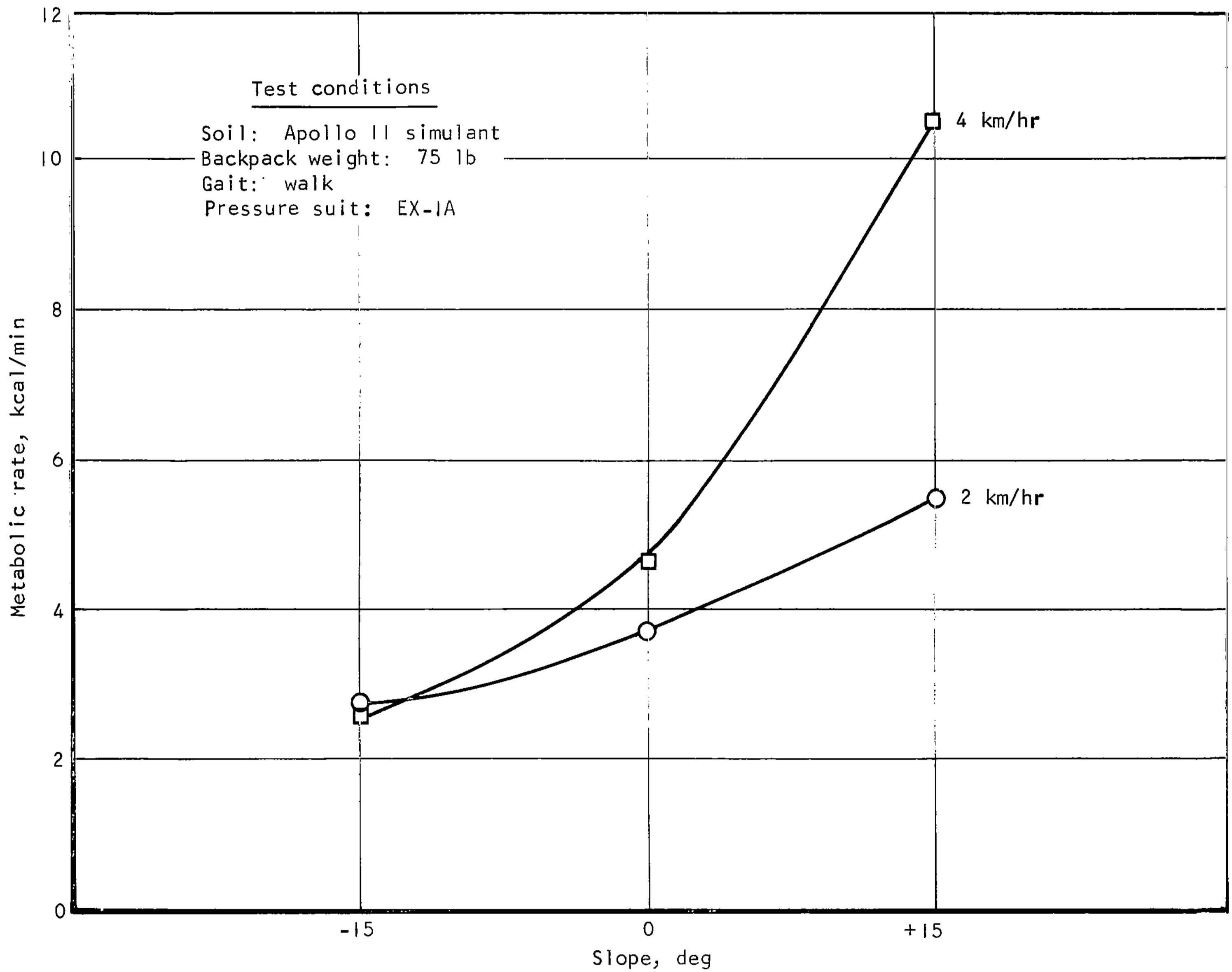


Fig. 4-7. Metabolic rate versus slope for various velocities

TABLE 4-18.-- INDIVIDUAL VALUES OF CARBON DIOXIDE PRODUCTION

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Carbon dioxide production, liters/min-STPD, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	0.646 0.717	0.925 0.625				
RW RB	0	75	Run			1.442 0.761	1.271 0.986		
RW RB	0	75	Lope					1.785 1.282	1.566 0.993
RW RB	+15	75	Walk	0.457 1.184	1.029 1.646				
RW RB	-15	75	Walk	0.562 0.766	0.501 0.723				

TABLE 4-19.-- AVERAGE CARBON DIOXIDE PRODUCTION

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Carbon dioxide production, liters/min-STPD, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	0.682 ±0.050[a]	0.775 ±0.212				
0	75	Run			1.214 ±0.322	1.129 ±0.202		
0	75	Lope					1.534 ±0.356	1.280 ±0.405
+15	75	Walk	0.821 ±0.514	1.338 ±0.436				
-15	75	Walk	0.664 ±0.144	0.621 ±0.157				

[a]Mean ±1 standard deviation

TABLE 4-20.-- INDIVIDUAL VALUES OF OXYGEN CONSUMPTION

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Oxygen consumption, liters/min-STPD, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW	0	75	Walk	0.779	1.128				
RB				0.866	0.757				
RW	0	75	Run			1.755	1.547		
RB						0.920	1.197		
RW	0	75	Lope					2.154	1.570
RB								1.552	1.196
RW	+15	75	Walk	0.553	1.244				
RB				1.444	2.064				
RW	-15	75	Walk	0.684	0.609				
RB				0.933	0.877				

TABLE 4-21.-- AVERAGE OXYGEN CONSUMPTION

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Oxygen consumption, liters/min-STPD, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	0.823 ±0.062[a]	0.943 ±0.262				
0	75	Run			1.338 ±0.590	1.372 ±0.247		
0	75	Lope					1.853 ±0.426	1.383 ±0.264
+15	75	Walk	0.989 ±0.644	1.654 ±0.580				
-15	75	Walk	0.809 ±0.176	0.743 ±0.190				

[a]Mean ±1 standard deviation

TABLE 4-22.-- INDIVIDUAL VALUES OF MINUTE VENTILATION

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Minute ventilation, liters/min-BTPS, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	15.012 22.256	23.668 18.868				
RW RB	0	75	Run			37.329 24.134	33.492 29.576		
RW RB	0	75	Lope					47.816 35.118	50.374 32.232
RW RB	+15	75	Walk	35.449 28.649	55.871 40.672				
RW RB	-15	75	Walk	16.144 20.902	22.671 23.898				

TABLE 4-23.-- AVERAGE MINUTE VENTILATION

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Minute ventilation, liters/min-BTPS, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	18.634 ±5.122[a]	21.268 ±3.394				
0	75	Run			30.732 ±9.330	31.534 ±2.769		
0	75	Lope					41.467 ±8.979	41.303 ±12.828
+15	75	Walk	32.049 ±4.808	48.272 ±10.747				
-15	75	Walk	18.523 ±3.36	23.285 ±0.868				

[a]Mean ±1 standard deviation

TABLE 4-24.-- INDIVIDUAL VALUES OF RESPIRATORY RATE

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Respiratory rate, breaths/min, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	19.3 22.8	21.0 22.8				
RW RB	0	75	Run			21.8 24.4	21.9 23.7		
RW RB	0	75	Lope					29.8 24.5	27.1 24.2
RW RB	+15	75	Walk	21.2 23.1	27.1 25.8				
RW RB	-15	75	Walk	23.5 18.0	18.7 23.2				

TABLE 4-25.-- AVERAGE RESPIRATORY RATE

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Respiratory rate, breaths/min, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	21.1 ±2.5[a]	21.9 ±1.3				
0	75	Run			23.1 ±1.8	22.8 ±1.3		
0	75	Lope					27.2 ±3.7	25.7 ±2.1
+15	75	Walk	22.1 ±1.3	26.5 ±0.9				
-15	75	Walk	20.8 ±3.9	21.0 ±3.2				

[a]Mean ±1 standard deviation

TABLE 4-26.--INDIVIDUAL VALUES OF RECTAL TEMPERATURE

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Rectal temperature, °F, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	98.3 99.4	98.6 99.2				
RW RB	0	75	Run			99.1 99.5	99.4 99.7		
RW RB	0	75	Lope					99.8 99.3	99.1 99.9
RW RB	+15	75	Walk	98.6 99.3	99.3 98.8				
RW RB	-15	75	Walk	99.6 99.8	98.6 99.6				

TABLE 4-27.-- AVERAGE RECTAL TEMPERATURE

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Rectal temperature, °F, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	98.9 ±0.8[a]	98.9 ±0.4				
0	75	Run			99.3 ±0.3	99.6 ±0.2		
0	75	Lope					99.6 ±0.4	99.5 ±0.6
+15	75	Walk	99.0 ±0.5	99.1 ±0.4				
-15	75	Walk	99.7 ±0.1	98.8 ±1.1				

[a]Mean ±1 standard duration

TABLE 4-28.-- INDIVIDUAL VALUES OF STEP RATE

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Pack weight, lb	Gait	Step rate, steps/min, at --					
				2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
RW RB	0	75	Walk	66 60	102 84				
RW RB	0	75	Run			120 114	120 114		
RW RB	0	75	Lope					48 78	54 84
RW RB	+15	75	Walk	84 60	114 102				
RW RB	-15	75	Walk	48 48	90 60				

TABLE 4-29.-- AVERAGE STEP RATE

[Self-locomotion; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Pack weight, lb	Gait	Step rate, steps/min, at --					
			2 km/hr	4 km/hr	6 km/hr	8 km/hr	6 km/hr	8 km/hr
0	75	Walk	63.0 ±4.2[a]	93.0 ±12.7				
0	75	Run			117.0 ±4.2	117.0 ±4.2		
0	75	Lope					63.0 ±21.2	69.0 ±21.2
+15	75	Walk	72.0 ±17.0	108 ±8.5				
-15	75	Walk	48.0 ±0	75.0 ±21.2				

[a]Mean ±1 standard location

CART PULLING ON AN APOLLO 11 SOIL SIMULANT

General

Section 2 describes the design, construction and simulation techniques used for the tests to evaluate the metabolic costs of pulling a cart in simulated lunar gravity on a simulated lunar soil. Problems presented by forces required for grasping in pressure gloves were solved by a V-frame (fig. 2-27) on the cart handles and by adjusting the cart center-of-gravity so that a slight weight was applied on the handles. Thus the weight was carried in the normal curl of the fingers and most of the pulling force was applied to the edge of the hand. The safety cord seen in fig. 2-27 prevents one hand from slipping loose which would cause the cart to veer to one side.

Metabolic Rates

The metabolic rates obtained during the various tests are presented in tables 4-30 and 4-31. The data shown in table 4-31 are presented graphically in figs. 4-8 and 4-9. The data for traversing the Apollo 11 soil on a 0^0 slope with a 75-lb backpack (table 4-17) is not appreciably different from the data for pulling a 165-lb cart on the same soil and at the same 0^0 slope (table 4-31). The lack of an additional cost for pulling the cart over the cost of locomotion without the cart is not understood. The absence of an additional cost needs clarification and additional tests are required to evaluate the real effects of cart pulling. Increasing the cart weight to 325 lb increased the metabolic cost of locomotion.

Locomotion on the slopes had the most dramatic effect on metabolic rates. Metabolic rates were much higher than expected for ascending a 15^0 slope. The cost at 2 km/hr is extremely high and the subjects were unable to perform at higher velocities; therefore, tests were performed at 1 km/hr to provide data at an additional rate. In descending the 15^0 slope, the data indicate that the cart was pushing the subjects downhill. This is confirmed by the pull-force data of fig. 2-30 which shows that the pull force becomes negative while descending the 15^0 slope.

These exploratory test indicate that the use of a cart on the lunar surface is feasible providing uphill grades are avoided. Cart stability problems may be encountered on descending grades, depending on whether the cart is pulled or pushed by the individual. Cart push tests were not made. The mechanics of pulling a cart are not completely understood. Therefore, the design of the cart, the choice of loads, and adjustment of the cart center-of-gravity were completely arbitrary as were the wheel and handle designs.

Carbon Dioxide Production, Oxygen Consumption, and Minute Ventilation

Carbon dioxide production, oxygen consumption, and minute ventilation are shown in tables 4-32 and 4-33, tables 4-34 and 4-35, and tables 4-36 and 4-37, respectively. The relationships described for metabolic rates apply to these variables.

Respiratory Rates and Rectal Temperature

Respiratory rates are presented in tables 4-38 and 4-39. Rectal temperatures are given in tables 4-40 and 4-41. Respiratory rates were within the expected range for all measured metabolic rates except for ascending a 15^{0} slope. Respiratory rates for a $+15^{0}$ slope were greatly increased as a function of the high metabolic rate measured. There were no statistical differences noted in rectal temperature during any test or between any test modes.

Stepping Rate

Step rates for each test performed while pulling a cart are reported in tables 4-42 and 4-43. There is a tendency for the stepping rate to be lower for any given velocity while pulling a cart as compared to locomotion without a cart on either the coarse lunar or Apollo 11 lunar soil simulants. This indicates that the stride length was increased while pulling a cart.

It was also noted that the subjects leaned into the direction of movement to produce a force vector to enable him to pull the cart and to transfer the pulling force down the skeleton to the feet rather than accept the full load on the muscle mass of the arms and shoulders. The kinematics of pulling a cart are not understood and will require further study.

TABLE 4-30.-- INDIVIDUAL VALUES OF METABOLIC COST

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Cart weight, lb	Gait	Metabolic cost, kcal/min, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		3.37 3.23	4.33 3.69	4.84 4.54	5.50 6.29
RB RW	0	325	Walk		4.25 4.07	5.26 5.84	5.60 5.96	8.82 8.35
RB RW	+15	165	Walk	11.66 6.19	15.27 10.67			
RB RW	+15	325	Walk	9.64 7.90	15.16 13.51			
RB RW	-15	165	Walk		1.61 1.58		1.93 3.19	
RB RW	-15	325	Walk		2.18 1.58		2.39 2.23	

TABLE 4-31.-- AVERAGE METABOLIC COST

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Metabolic cost, kcal/min, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		3.30 ±0.10[a]	4.01 ±0.45	4.69 ±0.21	5.90 ±0.56
0	325	Walk		4.16 ±0.13	5.55 ±0.41	5.78 ±0.25	8.59 ±0.33
+15	165	Walk	8.93 ±3.87	12.97 ±3.25			
+15	325	Walk	8.77 ±1.23	14.34 ±1.17			
-15	165	Walk		1.74 ±0.18		2.56 ±0.89	
-15	325	Walk		1.88 ±0.42		2.31 ±0.11	

[a]Mean ±1 standard duration

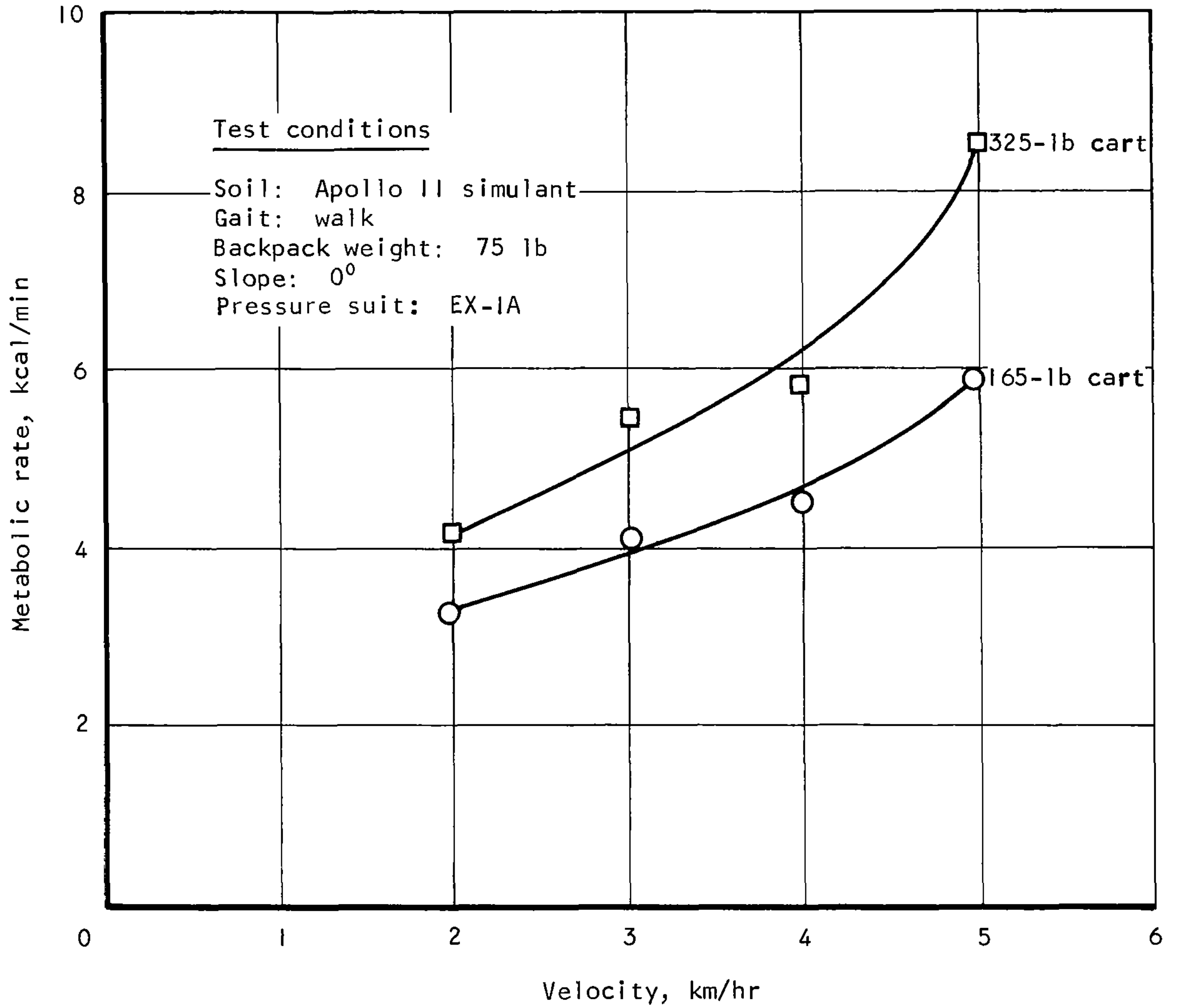


Fig. 4-8. Metabolic rate versus velocity for various cart weights

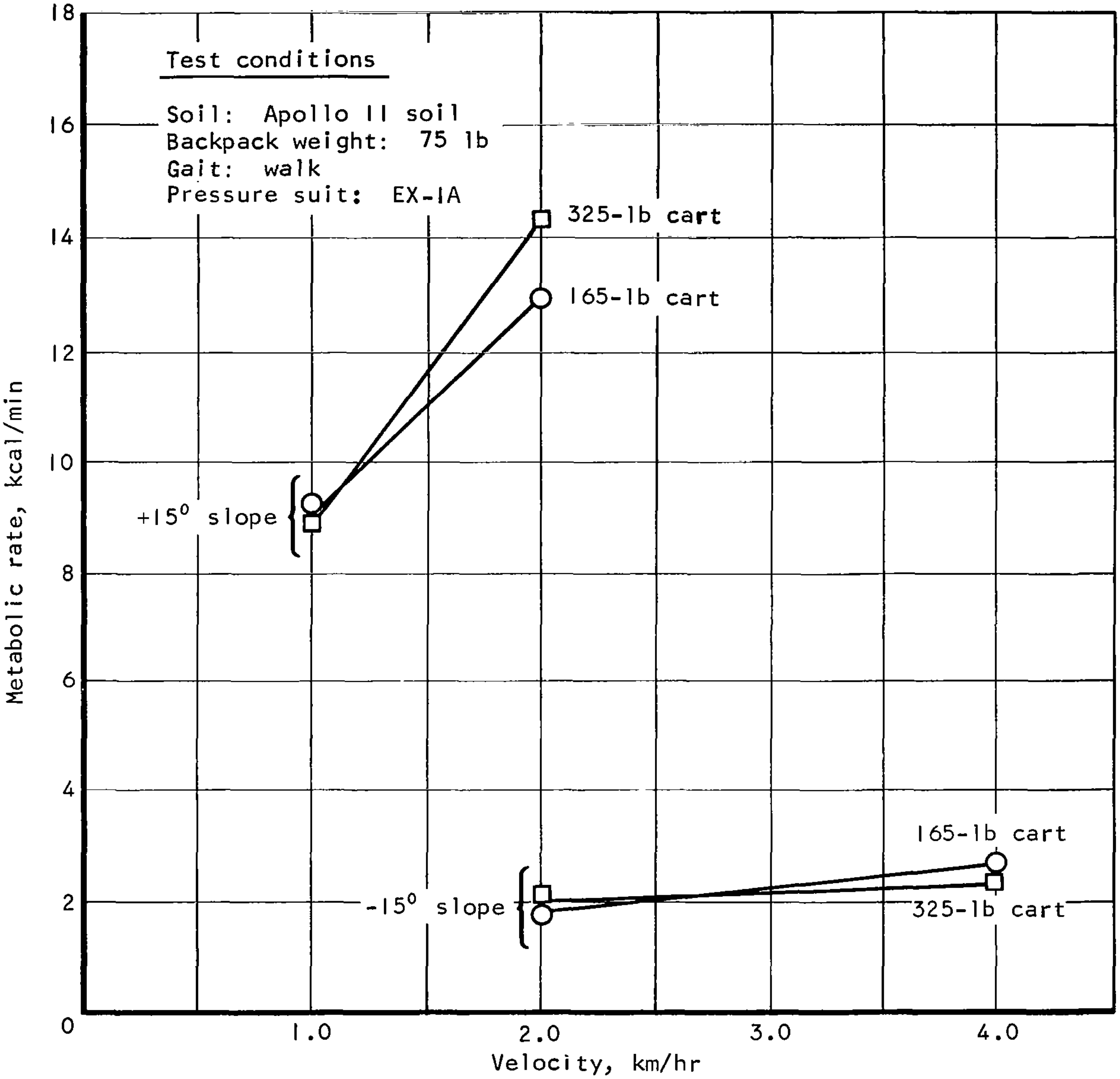


Fig. 4-9. Metabolic rate versus velocity for various cart weights and slopes

TABLE 4-32.-- INDIVIDUAL VALUES OF CARBON DIOXIDE PRODUCTION

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Cart weight, lb	Gait	Carbon dioxide production, liters/min-STPD, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		0.578 0.377	0.370 0.779	0.944 0.579	0.897 1.006
RB RW	0	325	Walk		0.721 0.702	0.894 0.993	1.046 1.075	1.533 1.386
RB RW	+15	165	Walk	1.989 0.858	2.667 1.811			
RB RW	+15	325	Walk	1.248 1.286	2.659 2.255			
RB RW	-15	165	Walk		0.317 0.292		0.512 0.327	
RB RW	-15	325	Walk		0.247 0.370		0.354 0.407	

TABLE 4-33.-- AVERAGE CARBON DIOXIDE PRODUCTION

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Carbon dioxide production, liters/min-STPD, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		0.478 ±0.142[a]	0.575 ±0.289	0.762 ±0.258	0.943 ±0.090
0	325	Walk		0.712 ±0.013	0.943 ±0.070	1.061 ±0.021	1.460 ±0.104
+15	165	Walk	1.424 ±0.800	2.239 ±0.605			
+15	325	Walk	1.267 ±0.027	2.475 ±0.311			
-15	165	Walk		0.305 ±0.018		0.420 ±0.131	
-15	325	Walk		0.309 ±0.087		0.381 ±0.037	

[a]Mean ±1 standard duration

TABLE 4-34.-- INDIVIDUAL VALUES OF OXYGEN CONSUMPTION

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Cart weight, lb	Gait	Oxygen consumption, liters/min-STPD, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		0.697 0.454	0.446 0.941	1.136 0.698	1.084 1.216
RB RW	0	325	Walk		0.870 0.856	1.092 1.211	1.261 1.296	1.853 1.425
RB RW	+15	165	Walk	2.413 1.047	3.17 2.211			
RB RW	+15	325	Walk	1.515 1.569	3.238 2.749			
RB RW	-15	165	Walk		0.384 0.356		0.622 0.399	
RB RW	-15	325	Walk		0.299 0.496		0.429 0.496	

TABLE 4-35.-- AVERAGE OXYGEN CONSUMPTION

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Oxygen consumption, liters/min-STPD, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		0.576 ±0.172[a]	0.694 ±0.350	0.917 ±0.309	1.150 ±0.093
0	325	Walk		0.863 ±0.099	1.152 ±0.084	1.279 ±0.025	1.639 ±0.303
+15	165	Walk	1.730 ±0.966	2.695 ±0.684			
+15	325	Walk	1.542 ±0.038	2.994 ±0.346			
-15	165	Walk		0.370 ±0.020		0.511 ±0.158	
-15	325	Walk		0.398 ±0.139		0.463 ±0.047	

[a]Mean ±1 standard deviation

TABLE 4-36.-- INDIVIDUAL VALUES OF MINUTE VENTILATION

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Cart weight, lb	Gait	Minute ventilation, liters/min-BTPS, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		22.410 22.429	27.213 29.752	42.589 31.177	46.908 47.416
RB RW	0	325	Walk		22.476 21.476	26.046 26.576	32.406 30.992	44.349 42.538
RB RW	+15	165	Walk	35.400 27.837	50.971 52.793			
RB RW	+15	325	Walk	26.349 46.127	51.572 86.864			
RB RW	-15	165	Walk		10.446 9.593		16.552 11.623	
RB RW	-15	325	Walk		8.007 18.714		11.904 16.165	

TABLE 4-37.-- AVERAGE MINUTE VENTILATION

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Minute ventilation, liters/min-BTPS, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		22.420 ±0.013[a]	28.483 ±1.795	36.883 ±8.070	47.162 ±0.359
0	325	Walk		21.976 ±0.707	26.311 ±0.375	31.699 ±1.000	43.444 ±1.281
+15	165	Walk	31.619 ±5.348	51.882 ±1.288			
+15	325	Walk	36.238 ±13.985	69.218 ±24.955			
-15	165	Walk		10.020 ±0.603		14.088 ±3.485	
-15	325	Walk		13.361 ±7.571		14.035 ±3.013	

[a]Mean ±1 standard deviation

TABLE 4-38.-- INDIVIDUAL VALUES OF RESPIRATORY RATE

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Cart weight, lb	Gait	Respiratory rate, breaths/min, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		20.0 16.9	21.7 20.1	26.1 20.1	25.7 25.9
RB RW	0	325	Walk		19.9 21.5	22.6 21.8	21.9 21.6	23.8 22.7
RB RW	+15	165	Walk	25.3 27.3	31.5 30.8			
RB RW	+15	325	Walk	24.7 25.6	31.5 40.6			
RB RW	-15	165	Walk		24.8 18.4		26.9 20.2	
RB RW	-15	325	Walk		25.9 23.7		24.9 24.5	

TABLE 4-39.-- AVERAGE RESPIRATORY RATE

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Respiratory rate, breaths/min, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		18.5 ±2.2[a]	20.9 ±1.1	23.1 ±4.2	25.8 ±0.1
0	325	Walk		20.7 ±1.1	22.2 ±0.6	21.8 ±0.2	23.3 ±0.8
+15	165	Walk	26.3 ±1.4	31.2 ±0.5			
+15	325	Walk	25.2 ±0.6	36.1 ±6.4			
-15	165	Walk		26.6 ±2.5		23.6 ±4.7	
-15	325	Walk		24.8 ±1.6		24.7 ±0.3	

[a]Mean ±1 standard deviation

TABLE 4-40.-- INDIVIDUAL VALUES OF RECTAL TEMPERATURE

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subject]

Subject	Slope, deg	Cart weight, lb	Gait	Rectal temperature, °F, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		99.5 100.8	99.6 100.1	99.7 99.0	99.3 98.8
RB RW	0	325	Walk		99.9 100.6	98.9 101.0	100.2 100.0	99.9 99.4
RB RW	+15	165	Walk	100.2 99.4	100.2 99.4			
RB RW	+15	325	Walk	99.0 98.7	99.4 99.3			
RB RW	-15	165	Walk		99.2 98.3		99.0 98.4	
RB RW	-15	325	Walk		99.7 98.6		98.7 98.5	

TABLE 4-41.-- AVERAGE RECTAL TEMPERATURE

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Rectal temperature, °F, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		100.2 ±0.9[a]	99.9 ±0.4	99.4 ±0.5	99.1 ±0.4
0	325	Walk		100.3 ±0.5	100.0 ±1.5	100.1 ±0.1	99.7 ±0.4
+15	165	Walk	99.8 ±0.6	99.8 ±0.6			
+15	325	Walk	98.9 ±0.2	99.4 ±0.1			
-15	165	Walk		98.8 ±0.6		98.7 ±0.4	
-15	325	Walk		99.2 ±0.8		98.6 ±0.1	

[a]Mean ±1 standard deviation

TABLE 4-42.-- INDIVIDUAL VALUES OF STEP RATE

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Subject	Slope, deg	Cart weight, lb	Gait	Step rate, steps/min, at --				
				1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
RB RW	0	165	Walk		66 66	72 78	78 108	120 114
RB RW	0	325	Walk		60 60	84 78	108 114	102 96
RB RW	+15	165	Walk	48 69	78 90			
RB RW	+15	325	Walk	54 81	66 108			
RB RW	-15	165	Walk		54 60		66 72	
RB RW	-15	325	Walk		48 54		63 72	

TABLE 4-43.-- AVERAGE STEP RATE

[Test subject pulling a cart and carrying a simulated 75-lb backpack; Apollo 11 soil simulant; simulated lunar gravity; EX-1A pressure suit without ITMG; two test subjects]

Slope, deg	Cart weight, lb	Gait	Step rate, steps/min, at --				
			1 km/hr	2 km/hr	3 km/hr	4 km/hr	5 km/hr
0	165	Walk		66.0 ±0.0[a]	75.0 ±4.2	93.0 ±21.2	117 ±4.2
0	325	Walk		60.0 ±0.0	81.0 ±4.2	111.0 ±4.2	99.0 ±4.2
+15	165	Walk	58.5 ±14.8	84.0 ±8.5			
+15	325	Walk	67.5 ±19.1	87.0 ±29.7			
-15	165	Walk		51.0 ±4.2		69.0 ±4.2	
-15	325	Walk		51.0 ±4.2		67.5 ±6.4	

[a]Mean ±1 standard deviation

COMPARISONS BETWEEN THE EX-1A AND OTHER PRESSURE SUITS

Since these studies were exploratory in nature and only two subjects were studied, the comparisons made here may not be entirely valid. However, they are made to provide some indication as to the possible differences between suits.

Fig. 4-10 compares the energy cost of locomotion in an A-7L pressure suit with the cost for the EX-1A suit. The comparisons drawn between modes in the A-7L suit in ref. 3 showed that the energy cost for locomotion on a hard surface on an inclined plane simulator was lower than for either surface used with the turbine-operated vertical suspension simulation (TOSS) ($p < 0.08$). Locomotion costs on a coarse lunar soil simulant in TOSS were consistently higher at each velocity when compared to locomoting on a hard surface in the same simulator. These differences were not statistically different. Metabolic rates for the EX-1A suit on either lunar soil simulant are consistently lower than for the A-7L on the coarse lunar soil simulant. It should be remembered, however, that the A-7L was tested with the integrated thermal meteorite garment attached while the EX-1A was tested without an ITMG. The same loads were carried in all tests.

Fig. 4-11 compares several suits studied during simulated lunar gravity testing. The A-7L values were not considered different from the G-2C values (refs. 4 and 5) and this was attributed to a degrading of the mobility of the basic A-7L garment by the addition of the ITMG. It is apparent that the energy cost on a 3-degrees-of-freedom inclined plane simulator is lower than on the 6-degrees-of-freedom vertical simulators for comparable velocities. The values seen for the RX-2 and A-5L (ref. 6) are lower because they were performed on an inclined plane simulator and without a load. In all other tests a simulated 75-lb load was used. Only during the A-7L and G-2C tests on the inclined plane simulator was a 75 lb mass added directly to the subjects. During the lunar gravity simulations using vertical simulators, only the weight field was simulated and the total mass was not added to the subject. In the case of the A-7L and G-2C studies on the turbine operated suspension simulator the weight was derived from the suspension system, hoses, etc. During the current study the subject-suit system was balanced to a 1/6-g weight and the appropriate 1/6-g weight added to the subject's back to provide a load equivalent to 75 lb. With the exception of the inclined plane simulator studies, the mass of the load was never simulated. Unpublished data from this laboratory indicates, however, that as long as the load does not affect the subject's center of gravity and the subject is traveling in a straight line, the weight that the subject has to propel is the major determinant of metabolic cost. Mass will become extremely important, however, if it effects the individual's balance, shifts his center of gravity, or if he must make turning movements. The exact role of changing the center of gravity of an individual during locomotion should be determined.

Fig. 4-11 tends to support the premise that the energy cost of locomotion in the EX-1A is lower than for other pressure suits under similar conditions. These lower costs could be attributed to the greater mobility in the EX-1A and the lower torque forces required for bending the various suit joints. Further testing is required to ascertain that the premise drawn above is true.

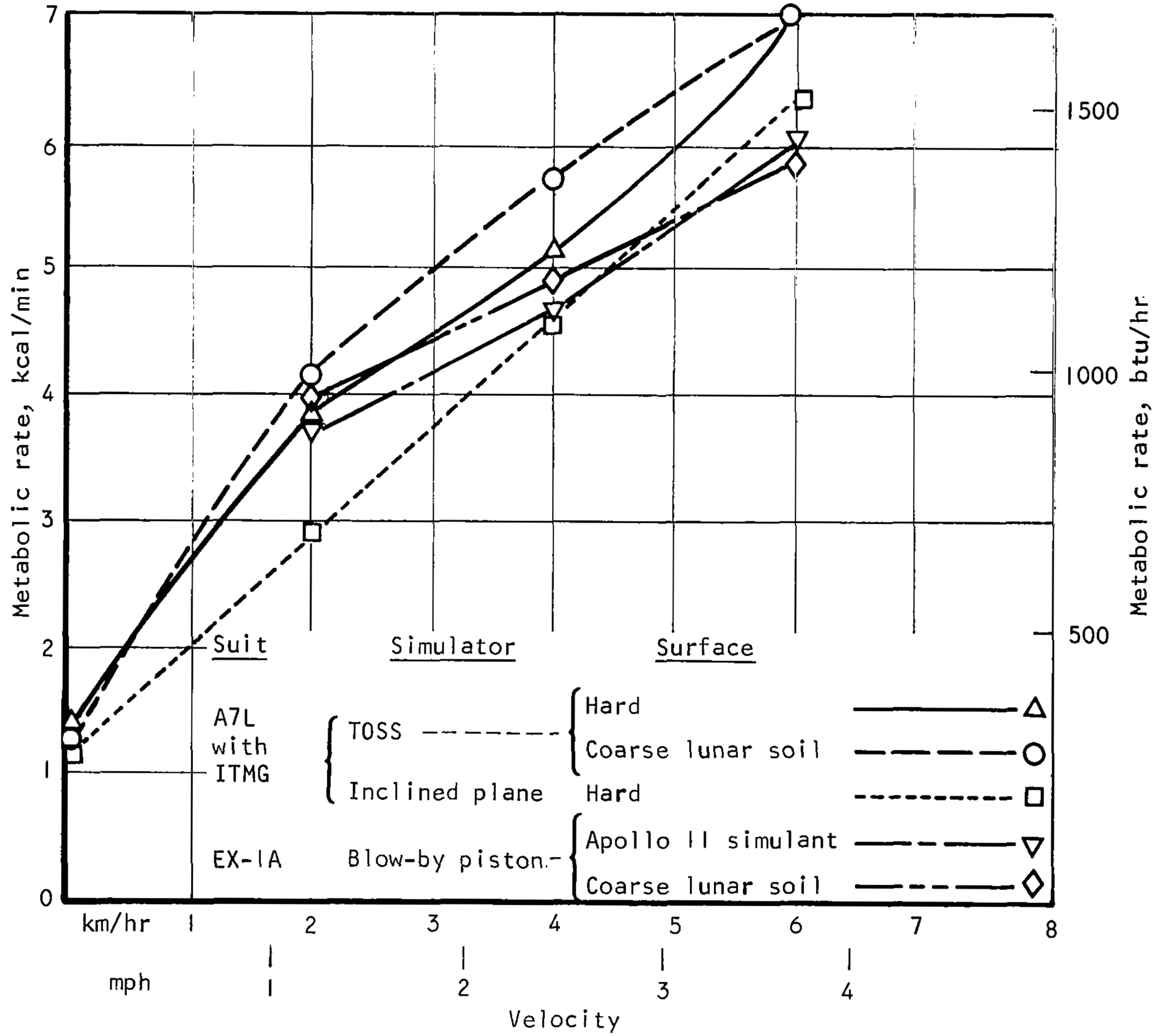


Fig. 4-10. Metabolic rate versus velocity for various suits, simulators, and surfaces

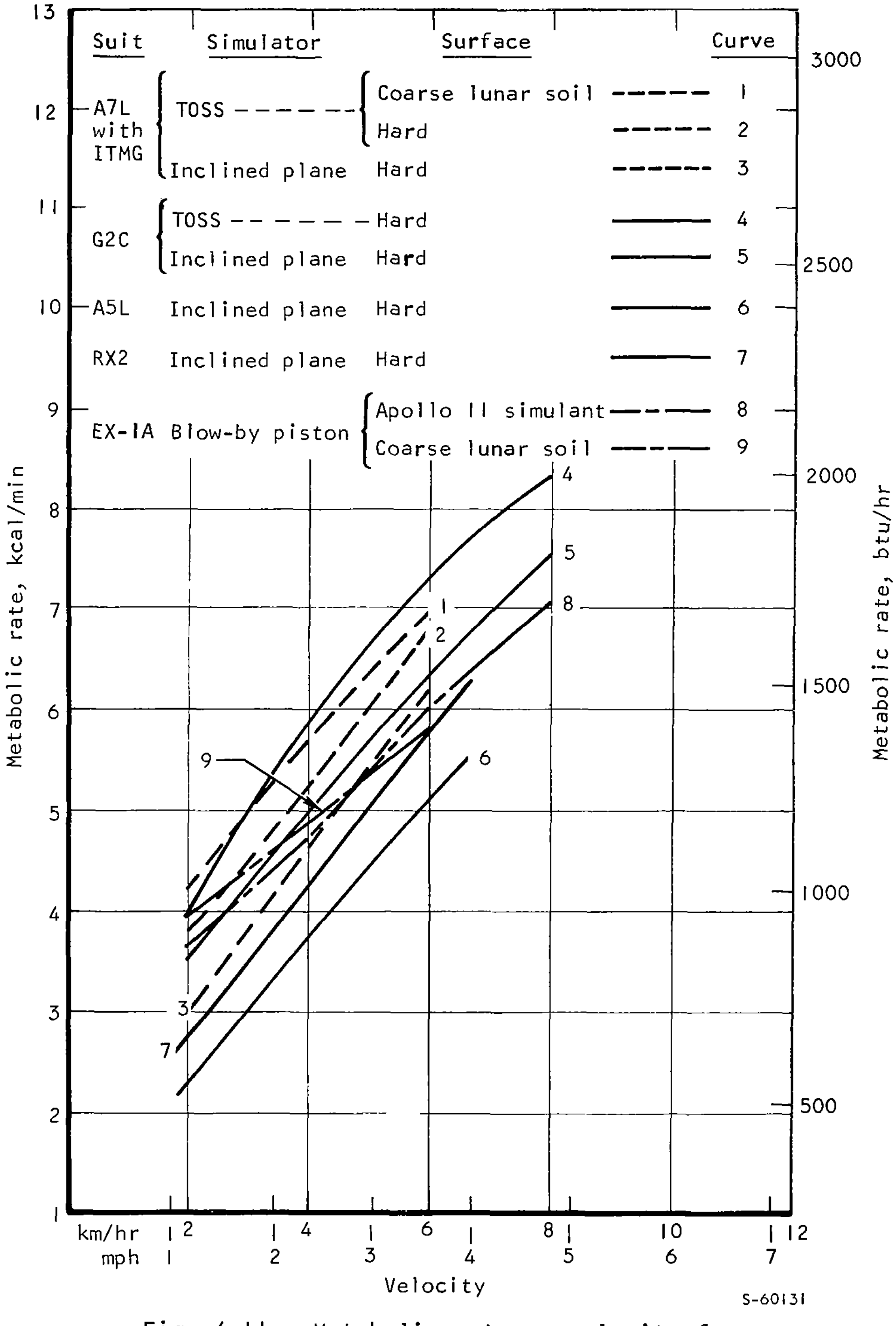


Fig. 4-11. Metabolic rate vs velocity for various suits, simulators and surfaces

SECTION 5.-CONCLUSIONS

The conclusions presented below are drawn with reservations since only two subjects were used in testing. The conclusions drawn are not based on statistical inference but are based on trends in the data.

(1) Pressure suits which incorporate a waist joint for flexion require special handling during decreased gravity simulations if the simulation is to be valid.

(2) The blow-by piston vertical suspension simulator represents the best dynamic simulator yet tested by this laboratory.

(3) In general, the metabolic cost of locomotion on the coarse lunar soil simulant are increased with velocity, load carrying, and ascending slopes.

(4) The metabolic cost of ascending a 15° slope was excessive, and neither subject was able to traverse such a slope at 4 km/hr.

(5) The energy cost of descending a slope with the coarse lunar soil simulant are lower than for walking on a level surface regardless of the load carried.

(6) Energy requirements were increased, as expected, on the Apollo 11 soil simulant with an increase in speed of locomotion.

(7) There were no apparent differences in metabolic costs for subjects carrying a 75-lb pack and locomoting on a level surface composed of either the coarse lunar or Apollo 11 soil simulants.

(8) The metabolic cost of traversing a 0° slope on the Apollo 11 soil with a 75-lb backpack and pulling a 165-lb cart did not show any discernable differences from that obtained with a 75-lb backpack alone. This lack of difference is not understood.

(9) Increasing the cart weight to 325 lb increased the metabolic cost of locomotion on the Apollo 11 soil simulant.

(10) Pulling a cart up a 15° slope resulted in an extremely high metabolic cost, and the subjects were barely able to perform the task at 2 km/hr.

(11) The metabolic rates obtained while descending a 15° slope indicated that the cart was pushing the subject downhill and this is confirmed by the pull-force data.

(12) Additional testing is required on a larger subject propulation to validate the above conclusions. Further testings with pulling and pushing a cart are necessary to understand the physiological costs of different configurations in cart design, including weight distribution

of the cart, methods of pulling or pushing, effects of changing direction, etc.

AiResearch Manufacturing Company,
Los Angeles, California, July 1, 1970.

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